Distributed ReStart

Energy restoration for tomorrow

DRZC Factory Acceptance Testing 1 Report by GE Digital

April 2022

In partnership with:

DRZC FAT 1 Test Report – Proof of Concept initial findings

Executive Summary

Distributed ReStart is an NIC funded innovation project that is developing a new approach to electricity system restoration using distributed energy resources (DERs). We have produced a functional specification for a Distribution Restoration Zone Controller (DRZC) system that will provide coordinated control of DERs in a network area.

We have commissioned the development and testing of a prototype DRZC by GE.

The GE report presents the results of the successful Factory Acceptance Testing (FAT) of the prototype DRZC within a Hardware-in-the-Loop (HiL) test environment. The report describes the test environment (including associated modelling), test procedures, test results and related conclusions. The FAT was performed within GE premises using an Opal-RT simulator, against a model based on network data provided by SP Energy Networks (SPEN).

The main output from the Distributed ReStart project related to the DRZC was to specify a set of generic technology functional requirements.

The intention of the build and test stage is to demonstrate viability beyond a "paper-based" functional design specification, while not indicating a preference for a specific design or vendor. The functional requirements of a DRZC proposed in "Assessment of Power Engineering – Aspects of Black Start from DER Part 2 – December 2020" could be updated based on the outcome of the tests.

The GE report provides useful information on the test environment and modelling that could inform future development and testing of smart network control solutions–as will be required for a transition to a net zero network.

This includes details of the HiL test facilities and communication interfaces between different components. The real-time simulation model includes the electrical network, a synchronous generator, wind farms, battery energy storage, and loads. This detailed modelling of the power system enables more thorough testing of the DRZC than using simple signal injection tests.

The tests covered all stages of a possible distribution restoration process from anchor generator start-up and network initialisation, through transformer energisation, load pickup and power island balancing, to resynchronisation and termination of island operation. The tests included the application of various disturbances to show how the DRZC responds. Each of the tests is described in detail in terms of set-up, procedure and verification of outcomes, including plots illustrating the behaviour of DRZC operation.

DRZC FAT 1 Test Report – Proof of Concept initial findings

The tests were all completed successfully, and the report provides important evidence of the viability of a DRZC system and the distribution restoration concept. The report also includes considerations for future work, highlighting opportunities for improvement and factors to be addressed when implementing this type of solution.

Included in the appendices are a series of short assessments of the viability of the communications and cyber-security designs that were proposed in our "Organisational, Systems and Telecommunications Design Stage II, December 2020" report. In summary, these include a specification of the communication strategies used in the designs for a distribution restoration solution. It describes a desktop-based study achieved by performing a penetration testing technique to the designs. The desktop study aids our understanding of potential attack vectors for the proposed communications, networks, and data, highlighting the ways an attacker may exploit any entry point to the system. It also discusses the communications design for distribution restoration, with a focus on cyber security requirements for the communication strategies. The appendices also provide the preliminary high-level scope for the test strategy proposal carried out by Pen Test Partners. This will be reviewed to provide further input on security testing to combine with the methodology in this report to form a complete test strategy proposal.

The final testing of the DRZC prototype will be within a Real Time Digital Simulator (RTDS) environment hosted at the National HVDC Centre. A sub-set of tests performed at the FAT stage will be executed against a dynamic model running on the Centre's RTDS.

SP Energy Networks (SPEN) are currently delivering a project, awarded as part of the Ofgem Green Recovery Fund (GRF), which will test the DRZC system on a section of a distribution and transmission network in Dumfries and Galloway, Southern Scotland. The project aims to include control of multiple DERs to demonstrate frequency management, as would be required within a Distribution Restoration Zone (DRZ).

On the completion of the remaining HiL testing by the Distributed Restart project, and a successful operational deployment (and test) by the SPEN Green Recovery Fund project, it is hoped that the concept will be further proven and lead to the adoption of a DRZC in the near future.

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DRZC FAT 1 Test Report

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GE Digital

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Glossary

Acronym	Description
ADMS	Advanced Distribution Management System combining Distribution and Outage Management Systems
BaU	Business as Usual
BESS	Battery Energy Storage System
CLPU	Cold Load Pick Up
DER	Distributed Energy Resource
DRZC	Distribution Restoration Zone Controller
FEP	Front End Processor
FIU	Field Interface Unit
GPS	Global Positioning Satellite
GTC	Group Tele Control
H	Generator inertia constant
HiL	Hardware-in-the-Loop
MITS	Main Interconnected Transmission System
NGESO	National Grid Electricity System Operator
NTP	Network Time Protocol
PBC	Primary Balancing Control
PhC	Phasor Controller
PMU	Phasor Measurement Unit
PR	Proportional Regulation
RoCoF	Rate of Change of Frequency
SBC	Secondary Balancing Control
SCADA	Supervisory Control And Data Acquisition
SPEN	Scottish Power Energy Networks
TO/TSO	Transmission Owner/Transmission System Operator
WAMS	Wide Area Management System

1 Introduction

The primary purpose of this document is to present evidence of the testing that has been carried out in the GE test environment. Further tests are planned in the HVDC Centre’s RTDS test environment, the results from that testing will be reported separately.

The DRZC system and the associated ADMS automation have been tested against a real-time dynamic model representation of the Chapelcross network in the OPAL-RT system. The testing was set up firstly to confirm that the DRZC system is operating correctly as designed. Further tests have been included to demonstrate the overall operation of the DRZC through planned and unplanned events in the controlled zone.

This document includes the following information:

1. A description of the test environment in which the tests were carried out
2. The network topology and the loading scenarios (see also Appendix A for load pickup scenarios)
3. An overview of the tests that were carried out
4. Description of the test process for each of the tests
5. A Communication Strategies Report
6. A Cybersecurity testing Report

2 Test Environment

This test report primarily describes the testing executed in the GE test environment including the OPAL-RT real-time dynamic simulator for Hardware-in-the-Loop (HiL) simulation based on the Chapelcross network.

A subsequent stage of testing will take place at the National HVDC Centre using an RTDS system. This testing stage may draw on the test plan described here. It should be noted that the model replica of the Chapelcross network used in RTDS and the OPAL-RT model have been developed independently.

The GE test environment is shown in Figure 1. It is described in more detail in the Detailed Design Specifications document. Essentially, it comprises

1. Advanced Distribution Management System (ADMS) for viewing, together with the Front End Processor (FEP) that manages controls and simulated network
2. A DRZC Controller to replicate the field device that manages the power balancing of the island
3. A PhC Field Interface Unit (FIU) Controller that interfaces between the controlled field devices the DRZC, and also the ADMS. It allows encrypted IEC104 protocol to be used in future, although only unencrypted IEC104 data will be used at the time of the testing.
4. PhasorPoint and a Phasor Data Concentrator (PDC), enabling the dynamic performance of the system to be recorded
5. OPAL-RT dynamic simulation environment that emulates the most relevant characteristics of the island operation.

The GE test environment uses GOOSE as the available control interface between OPAL-RT and PhC-FIU. This provides a fast interface for control signals to be applied to the real-time simulation and shows what can be achieved by control with low latency, and can be used to explore the effects of greater latency. In a real environment, the interfaces between PhC-FIU and plant would need to be a routable protocol such as R-GOOSE or IEC104, or hardwired I/O.

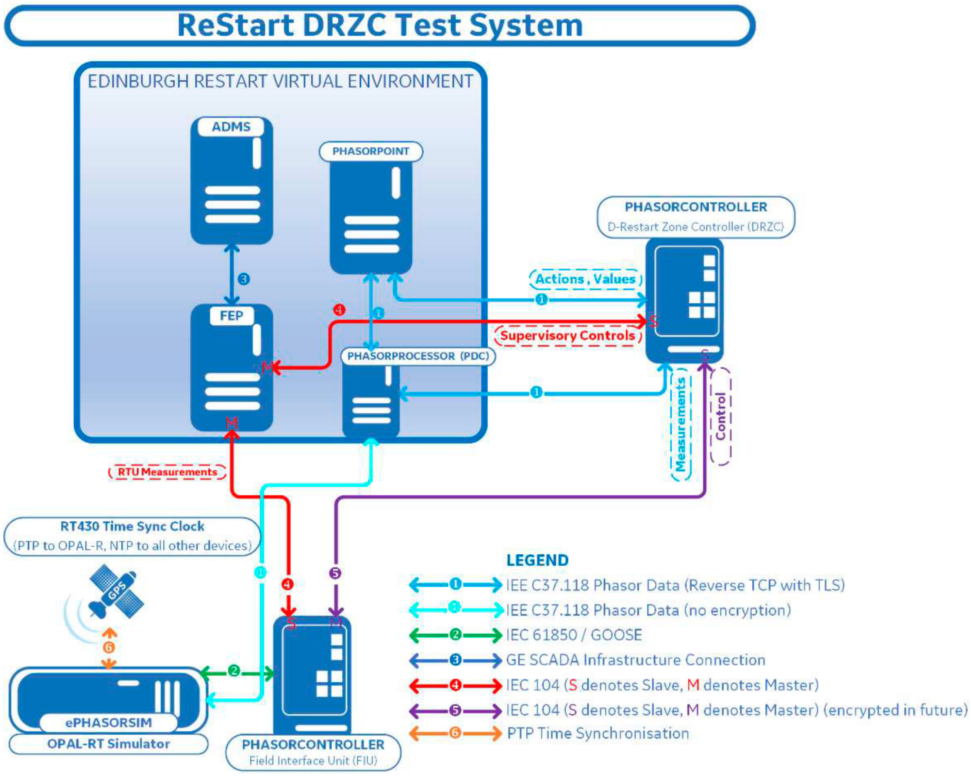


Figure 1 GE Hardware-in-the-Loop Testing Environment for the full DRZC Solution

The roles of PhasorPoint and PhasorProcessor in the system are as follows:

- PhasorProcessor is the Phasor Data Concentrator (PDC) that receives PMU data streams and makes it available to PhasorPoint applications and the historian.
- PhasorPoint is the WAMS software for analysing and visualizing PMU data
- The PhasorPoint system is used for acquisition, archiving and viewing dynamic data for review & analysis of the tests
- Automating repeatable test analysis is applied e.g. using Matlab to access, process and report test data using PhasorPoint's SQL interface to recorded data
- Real time visualization is provided for operator supervision requires dynamic views e.g. for the angle and frequency differences during the resynchronization process.
- PhasorPoint interprets data and passes on status values to ADMS e.g. confirming Anchor Generator / load bank load levels, stability and readiness.

The role of PhasorController as the core Distribution Restoration Zone Controller includes:

- Verifying operational states including running totals of PR, PBC, SBC1 & SBC2 resources relative to limits
- Triggering and applying fast and slow control as defined in Detailed Design
- Reporting information on the island state and resource availability via ADMS and PhasorPoint
- Determining/reporting current pickup capability with & without priming
- Providing information on actions taken by DRZC for logging and reporting in ADMS
- Flexible configuration for key analog & digital data
  - Dynamic data as C37.118 analogs & digitals to PhasorPoint
  - Steady state data over IEC104 to ADMS

3 Network and Loading Conditions

The test network is based on the Chapelcross network, but with the addition of a load bank at the anchor generator and a BESS at Minsca windfarm. The two windfarms at Minsca and Ewe Hill are assumed to be controllable resources. Load shedding can be applied at any of the feeders at Chapelcross 33kV breakers. In summary, the assumed resources are:

Proportional Regulation (PR)	Stevens Croft anchor generator (45MW)
Primary Balancing Control (PBC)	Load bank at Stevens Croft (-15MW)
	BESS at Minsca Windfarm – model for demo (+/-10MW)
Secondary Balancing Control (SBC1)	Minsca Windfarm (37MW)
	Ewe Hill Windfarm (12MW)
	Solwaybank Windfarm (30MW)
Secondary Balancing Control (SBC2)	Annan Primary (-2.9 to -10.0MW)
	Lockerbie/Kirkbank/Moffat (-4.6 to -18.0MW)
	Gretna/Langholm (-3.2 to -15.0MW)

The location of the PhC-DRZC is flexible and chosen based on available communications infrastructure. The PhC-DRZC should be located at a node with communications to all of the control points. In the case of the Chapelcross network (Figure 2), the central point of the communications is Chapelcross GSP rather than the anchor generator at Steven's Croft. With the DRZC located at Chapelcross GSP, the system could ride through loss of individual communications routes, while if the DRZC was located at Steven's Croft, loss of the communications route between Steven's Croft and Chapelcross GSP could leave only the anchor and load bank being controlled.

It would be possible (though out of the current project scope) to design logic at the anchor generator PhC-FIU to failover to a local mode of control for the anchor and load bank, allowing the DRZC to continue running with prediction of the operation of the anchor and loadbank.

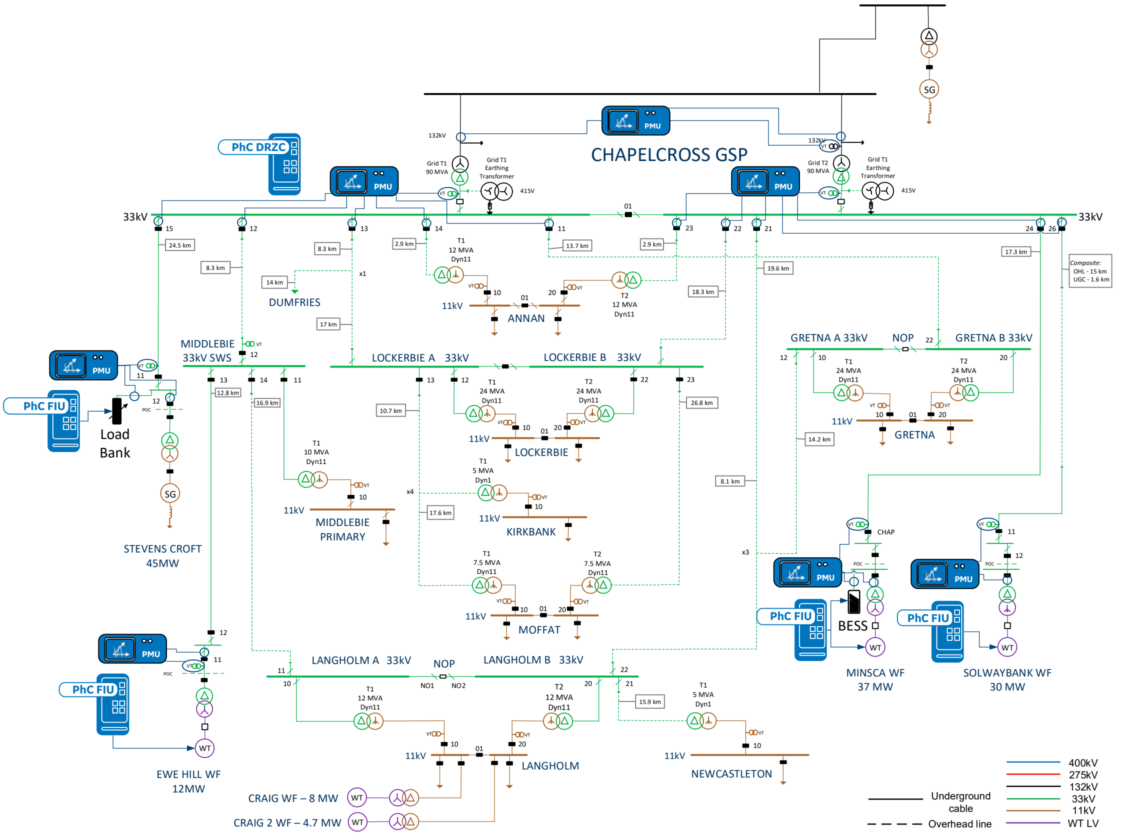


Figure 2 Chapelcross network with PMUs as basis for OPAL-RT dynamic model

3.1 Anchor Generator Modelling

The anchor generator is modelled as a synchronous machine with inertia, governor control and AVR/exciter control. The governor control is modelled with a power setpoint and frequency droop control. The governor model includes ramp rate limiters and time constants associated with the turbine model, which reflect the relatively slow response of the machine to changes in frequency

The model represents a round-rotor three-phase generator with parameters reported in Table 1. These are based on the parameters used in earlier dynamic simulations studies of the Chapelcross Distributed Restart process using DigSilent PowerFactory.

Table 1 Parameters for Steven’s Croft Anchor Generator

Synchronous Machine, General Parameters							
Rotor type: round				Nominal frequency: 50 Hz			
Number of Phases = 3				Connection: YN			
Nominal Apparent Power = 59.68 MVA		Nominal Voltage = 11 kV				Power Factor = 0.85	
Load Flow Parameters							
Reactive Power Limits		Zero Sequence Data			Negative Sequence Data		
Minimum Value	-29.84 Mvar (-0.5 p.u.)	x0	0.087 p.u.		x2	0.167 p.u.	
Maximum Value	41.776 Mvar (0.7 p.u.)	r0	0.00162 p.u.		r2	0.00162 p.u.	
Transient and Subtransients Parameters							
Time Constants				Reactances			
Td’’	0.031 s	Tq’’	0.074 s	xd’’	0.159 p.u.	xq’’	0.175 p.u.
Td’	0.878 s	Tq’	0.878 s	xd’	0.224 p.u.	xq’	0.403 p.u.
Tdc	0.312 s			Steady-State Shc. Current		1.2 p.u.	
Stator Parameters				Synchronous Reactances			
rstr	0.00162 p.u.			xd		1.88 p.u.	
xl	0.126 p.u.			xq		1.79 p.u.	

Table 2 presents the governor control and turbine parameters related to Steven's Croft anchor generator and Figure 3 shows the associated block diagram. During the model initialisation process, the model starts from a blackout scenario with the anchor generator disconnected from the grid and adjusted to follow an initial reference setpoint of 0.001 p.u. The output power of the governor acts once a frequency deviation is detected.

Table 2 Parameters for Steven's Croft Governor control and Turbine

Parameter	Description	Value
R	Frequency droop gain	0.01
T1	Steam chest time constant	0.3 s
T2	High pressure time constant	2.1 s
T3	Reheater time constant	35 s
Dt	Damping factor	0.2 p.u.
Vmax	Maximum limit for valve	1.1 p.u.
Vmin	Minimum limit for valve	0 p.u.

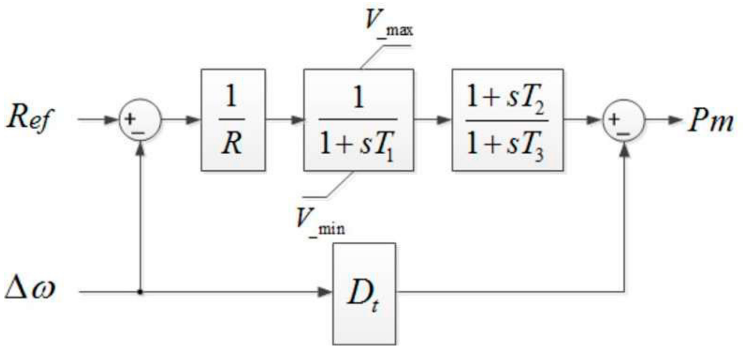


Figure 3 Governor control and Turbine block diagram

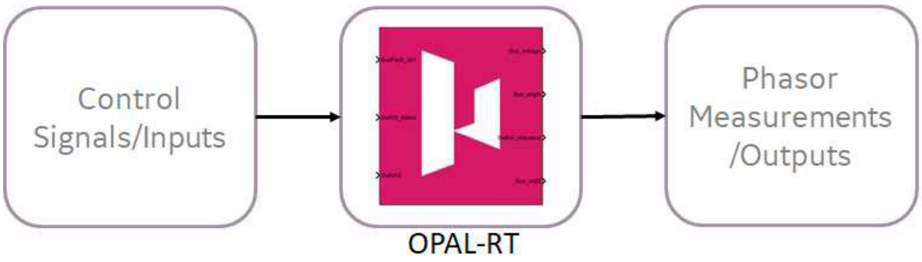


Figure 4 Modelling interface with Opal-RT

The synchronous machine and control elements have been modelled in Simulink/Matlab using built-in libraries from the ePHASORSIM RT-Lab, which it is compiled and loaded into the OPAL-RT for real-time simulation purposes. All the elements are defined using an excel input data file, and comprises conventional models presented in literature. The anchor generator is modelled as a sixth order round rotor machine, which includes the transient and sub-transient reactances, and damper windings on d-q axis.

In Simulink/Matlab, the network modelling is embedded into a solver block, which allows interfacing with control signals for adjusting setpoints or network reconfiguration. The block can also be configured to provide output signals.

3.2 Windfarm Modelling

The DER in the Chapelcross network are all wind generators and are modelled as negative loads with constant PQ. No frequency dependence is modelled.

A start-up profile for P&Q is assumed to represent the initial load as the windfarm is connected to the system and picks up output. The profile used for wind startup is described in Appendix B and illustrated in Figure 34. Once the bus is energised, there is a short delay with zero power until the windfarm commences its start-up when it draws a small load; the load was estimated to be 10% of the rated power of each plant. Once the warm-up/start-up sequence is complete, the unit will keep behaving as a load until a digital command is received from the DRZC to start ramping up to the minimum operating point of the windfarm. After that level is reached too, it is possible to start ramping up to different generation values.

A “power available” limit value is applied which varies over time with similar characteristics to the expected variation of wind. Power Available is an external signal to the DRZC, provided by the windfarm operator. It is assumed that this will be zero before and during start-up, rising to equal the minimum operating level once the start-up sequence is complete. Once the plant is ready to ramp up generation, Power Available will be updated to indicate the maximum dispatchable power.

Changes to the active and reactive setpoints initiated from the DRZC are programmed with a delay time and ramp rate limit, with the overall response being in the order of seconds to 10s of seconds.

3.3 Load Bank/BESS Modelling

Load bank and/or BESS are modelled as constant PQ loads, which in the BESS case can be positive or negative.

A delay time and ramp rate are modelled for setpoint changes. In contrast to DER modelling, the delay time and ramp rates are defined such that the overall response is in the sub-second timeframe.

3.4 Other Load Modelling

Loads are modelled as constant impedance which provides a realistic representation of load behaviour. A constant impedance load is less conservative than constant PQ in terms of the effect of disturbances on frequency but yields a more realistic overall frequency/ROCOF response with some voltage-based load relief occurring in addition to the inertial effect of the generator. There were also some computational issued identified in the Opal-RT solver for simulations using constant PQ loads through a blackout condition. The issue was resolved by applying constant impedance loads.

The time dependence of load includes:

1. Steady-state P & Q components
2. Pseudo-random small perturbations representing the natural noise in loads
3. Cold load pickup factor, typically 1.5x steady-state load
4. Settling time where load reduces linearly to steady-state level
5. Slow-trend common mode change of load over time, representing changes in demand and LV generation

Random perturbation of load is used to create realistic variations in frequency in island operation. This exercises the continuous action of Proportional Regulation (PR) control and demonstrates that the discrete actions of the DRZC are only activated on larger deviations. The random perturbation of load also stimulates the continuous frequency and angle variations that are expected for resynchronisation. Without this variation, the simulations may not produce a condition for synchrocheck breaker closure. The pseudo-random noise is filtered to represent relatively slow changes in the aggregated load at primary substations. The amplitude of the pseudo-random noise is typically no more than 5% of the steady-state level.

Cold load pickup will be larger than steady-state load due to thermostatic heating and refrigeration loads picking up simultaneously, motor loads starting, delay of LV generation restarting, etc. There is a discrete change in load expected about 20s from the cold load pickup as LV embedded generation automatically picks up. This may be initially a load increase followed shortly after by a load decrease as the units start to generate. Following this “demand bump”, the load will settle linearly to the steady-state value. The proposed load profile is shown in Appendix B, Figure 33.

In the real system, it is understood that load reduction from cold load pickup to 1x steady state would be around 30 minutes. However, to compress the timeframe for simulated tests, this can be reduced such that it is around 5-10 times larger than the settling time of the natural dynamics and closed loop controls. A load settling time compressed to around 3-4 minutes timeframe should ensure that the load reduction does not interact with the dynamics of the system, but this can be tuned.

The slow trend of steady-state load changes will be characterised using records taken from real distribution networks. Depending on the specific test requirements, a slow trend can be a load increase, a load decrease, or a load cycle. This can be used to exercise the slow balancing functions of the DRZC. As with cold load pickup and settling, the timeframe of steady-state load changes will be compressed by a factor of 10-15x so that test cases can be run without excessive wait times.

The following sub-section describes the data gathered on steady-state loading in the Chapelcross network. Other network load data is also where appropriate.

3.5 Load Modelling Statistical Characteristics

A year of primary load data was provided by SPEN to configure the network model to represent loading conditions that could be expected to occur in the network. Summaries of the data are provided in Table 3 where the load at each primary bus section is given, and in Table 4 where the total load of the primary is shown. There are options of picking up the feeder load in a single operation or picking up the individual bus sections.

Table 3 Statistical values of primary loads per bus section in 2018-19

	P1 MW			P2 MW			Q1 MVAR			Q2 MVAR		
	MAX	MEDIAN	MIN	MAX	MEDIAN	MIN	MAX	MEDIAN	MIN	MAX	MEDIAN	MIN
LANGHOLM	2.88	0.02	-5.23	2.42	-0.44	-6.59	1.88	0.05	-0.91	1.41	0.16	-0.69
MOFFAT	0.00	-0.87	-1.60	0.00	-1.18	-2.37	0.35	-0.03	-1.29	1.18	-0.04	-0.42
KIRKBANK	0.00	-0.87	-1.88				0.04	-0.15	-0.44			
GRETNA	0.00	-2.75	-6.70	0.00	0.00	-3.38	0.39	-0.14	-1.11	0.42	-0.07	-0.82
MIDDLEBIE	0.00	-2.49	-5.15				0.00	-0.29	-0.64			
NEWCASTLETON	0.95	0.50	0.00				0.12	0.04	0.00			
LOCKERBIE	0.00	-4.38	-7.21	-2.21	-4.72	-10.92	0.07	-0.94	-2.16	0.32	-0.66	-2.39
ANNAN	-1.44	-2.95	-5.62	-1.44	-2.91	-5.61	0.43	-0.17	-1.32	0.87	0.09	-0.83

NOTE: By convention, net load is a negative value and net generation is positive. Thus, the MIN value of power is most negative, and corresponds to the largest load. A positive value is net generation.

Table 4 Statistical values of total primary loads in 2018-19

	TOTAL P MW			TOTAL Q MVAR		
	MAX	MEDIAN	MIN	MAX	MEDIAN	MIN
LANGHOLM	**4.62**	-0.39	-10.89	**2.89**	0.15	-1.05
MOFFAT	0.00	-2.05	-3.74	0.24	-0.07	-0.46
KIRKBANK	0.00	-0.87	-1.88	0.04	-0.15	-0.44
GRETNA	0.00	-3.34	-6.70	0.11	-0.29	-1.18
MIDDLEBIE	0.00	-2.49	-5.15	0.00	-0.29	-0.64
NEWCASTLETON	0.95	0.50	0.00	0.12	0.04	0.00
LOCKERBIE	-4.62	-9.11	**-14.81**	0.23	-1.60	**-4.05**
ANNAN	-2.89	-5.87	-11.23	0.86	0.04	-1.74
CHAPELCROSS TOTAL	-11.85	-24.71	-45.93	2.77	-1.96	-7.01

The default loading cases for primary transformers are given in Table 5 through Table 7. In general, large load active power values (large negative) coincide with the higher values of reactive power, so it is assumed that the maximum active power values align with the minimum reactive power values and vice versa.

In the high load case in Table 5, the maximum primary load pickup is 14.81MW at Lockerbie, and this maximum is considered together with the maximum total Chapelcross GSP loading of 45.93MW. The maximum value across the whole year of data for Lockerbie is used to explore the maximum load pickup value. The largest load at Lockerbie does not coincide with the largest load at other feeders, so the other feeders are adjusted so that the maximum overall Chapelcross loading is reflected. The Lockerbie load may be split between the two buses to reduce the pickup value if required, and the largest load in one bus section is given.

Table 5 High load case (steady state values)

High load case	TOTAL		SPLIT BUS MAX	
	P MIN	Q MAX	P MIN	Q MAX
LANGHOLM	-9.68	1.78	-6.59*	1.41*
MOFFAT	-2.53	0.15		
KIRKBANK	-0.67	0.02		
GRETNA	-5.49	0.07		
MIDDLEBIE	-3.94	0.00		
NEWCASTLETON	1.21	0.07		
LOCKERBIE	-14.81	0.14	-10.92*	-2.21*
ANNAN	-10.02	0.53		
Chapelcross ALL	-45.93	2.77		

* Bus 2

A typical load case is provided using the median values of load throughout the year of data. The median is used in preference to the mean since the distribution of samples is asymmetric.

Table 6 Typical (median) load case (steady state values)

Median load case	TOTAL		SPLIT BUS MAX	
	P MEDIAN	Q MEDIAN	P MIN	Q MAX
LANGHOLM	-0.39	0.15	-0.44*	0.16*
MOFFAT	-2.05	-0.07		
KIRKBANK	-0.87	-0.15		
GRETNA	-3.34	-0.29		
MIDDLEBIE	-2.49	-0.29		
NEWCASTLETON	0.50	0.04		
LOCKERBIE	-9.11	-1.60	-4.72*	-0.66*
ANNAN	-5.87	0.04		
Chapelcross ALL	-23.61	-2.17		

* Bus 2

In the low load case in Table 7, there would be significant DER in the system and some of the values are positive, indicating power flowing back into the system (i.e. net generation at the primary).

Table 7 Low load case (steady state values)

Low load case	TOTAL	
	P MAX	Q MIN
LANGHOLM	4.62	-1.05
MOFFAT	0.00	-0.46
KIRKBANK	0.00	-0.44
GRETNA	0.00	-1.18
MIDDLEBIE	0.00	-0.64
NEWCASTLETON	0.95	0.00
LOCKERBIE	-4.62	-4.05
ANNAN	-2.89	-1.74
Chapelcross ALL	-1.93	-9.56

Note that the values given in Table 5 through Table 7 are the steady-state values of the load. In practice, the instantaneous load pickup value is significantly greater than the steady-state value. The assumption used in Phase 1 that the initial dynamic value of pickup is 1.5x the steady state expected value and reduces linearly to steady state level in 30 minutes.

4 Test Results

The testing process will follow a progression from testing focused on individual elements through to a series of "Full Process Walkthrough" tests of different scenarios. Tests are consistent with those stated in the Test Specification document.

The results are reported as follows:

1. All testing is documented by GE, with key measurements and actions recorded and described for review by the Distributed Restart engineering team. The results include time-series recordings of frequency, power, and voltage, along with the actions of the DRZC system. Events are reported in high resolution using the PhasorPoint WAMS system where appropriate. ADMS screenshots have been captured where appropriate.
2. Testing marked as "Customer Witnessed" have been run by GE with the Distributed Restart engineering team to demonstrate how the system would work in the live environment.

4.1 Overview of Completed Tests

Test #	Functionality being tested
1. Network initialisation and anchor start-up	
1.00	Zone Black identification from DRZC shown in PhasorPoint and ADMS
1.01	Zone Black identification from ADMS
1.02	Group Tele-Control for Network Initialisation
1.03	Observation of anchor start-up with ADMS and PhasorPoint
2. Island Balancing and Load Pickup	
2.00	Starting and stopping Fast and Slow Balancing from ADMS
2.01	Energising the GSP 33kV-side
2.02	Simple load pickup and trip events – Fast Balancing
2.03	Large load pickup with priming
2.04	Energising circuits with balancing resources and expanding DRZC controllable resources
2.05	Variations of DER and load power causing regulation and Slow Balancing actions
2.06	Multiple unplanned disturbance events including load and generator shedding
2.07	Demonstrate frequency level event responses and compare RoCoF triggering

3. Energising Transformers and Resynchronisation	
3.00	Energise 132/33kV transformers from 33kV side
3.01	Demonstrate resynchronising control and view in PhasorPoint
3.02	Demonstrate DRZC synchrocheck function
4. Termination of Island Operation	
4.00	Restore network to grid-connected mode using GTC
4.01	Display ongoing resource margins
5. Full Process Walk-through	
5.00	High-load, high power available scenario; energisation and load pickup to resynchronisation and termination without unplanned events.
5.01	Medium load, low power available scenario; energisation and load pickup up to resynchronisation and termination without unplanned events.
5.02	High-load, high power available scenario with unplanned load and generator tripping including multiple event sequences.
5.03	High-load, high power available scenario with unplanned network tripping.
5.04	Medium load, no wind available, no BESS at Minsca,
5.05	High load, no wind available, no BESS at Minsca,
5.06	Medium load, no wind available, BESS at Minsca operating.
5.07	High load, no wind available, BESS at Minsca operating.

4.2 Network initialisation and anchor start-up

In Stage 1, the network is reconfigured for blackstart using switching sequences and protection settings groups deployed from the ADMS. There is no DRZC involvement in Stage 1.

Test 1.00	**Zone Black identification from DRZC shown in PhasorPoint and ADMS**	
Set-up	Configure the OPAL-RT model with no generation running, no load and all zero voltages. Circuit breaker positions are configured typically for a post-blackout condition – most network circuit breakers closed, most generator circuit breakers open, with some exceptions. PMU data is valid. RTU data is zero volts at all 33kV and 11kV measurements. PMU data is valid and zero volts.	
1. Procedure	Zone black confirmation – PMUs - normal. Inspect the Zone Black status and validity determined by DRZC, shown as a digital value in PhasorPoint and confirm that the same status values can be observed in ADMS.	
2. Verification	Zone black digital status value and associated validity (zoneBlack, zoneBlackValid) should both be TRUE in PhasorController, PhasorPoint and in ADMS. ADMS GTC Network Initialisation status should be Ready.	☑
3. Procedure	Zone black confirmation – PMUs - exceptions. A series of test conditions to prove the cases of detecting non-zone-black conditions. After each condition, return to the default set-up case. To create an invalid measurement, use PhC Designer to force the validity metadata of a particular PMU measurement to FALSE in DRZC, rather than reading validity from the data stream. To create a valid non-zero critical measurement, energise the HV and LV sides of the 132/33 transformer. All 33kV line breakers open. To create a valid non-zero non-critical measurement, use PhC Designer to adapt an incoming PMU value in DRZC. Apply the following scenarios in sequence with each other: 1. Set the status of one of the critical PMUs to zero volts, invalid 2. Set the value of one of the critical PMUs to non-zero, valid 3. Set the value of one of the non-critical PMUs to non-zero volts, invalid 4. Set the value of one of the non-critical PMUs to non-zero volts, valid	

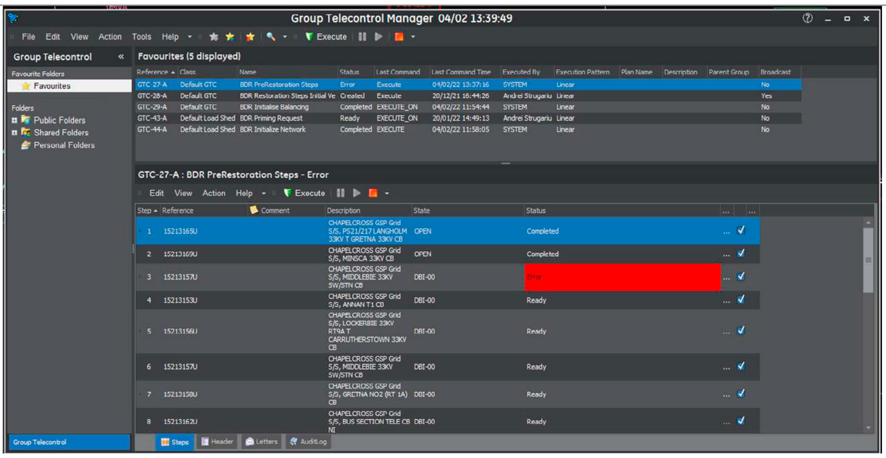
	Inspect the status of Zone Black status and validity determined by DRZC, shown as a digital value in PhasorPoint and confirm that the same status values can be observed in ADMS. Inspect the GTC status for Network Initialisation to check if status is Ready or Not Ready.	
4. Verification	Zone black digital status value and associated validity (zoneBlack, zoneBlackValid) in PhasorPoint and in ADMS should take the following values. 1. zoneBlack=FALSE; zoneBlackValid=FALSE 2. zoneBlack=FALSE; zoneBlackValid=TRUE 3. zoneBlack=TRUE; zoneBlackValid=TRUE 4. zoneBlack=FALSE; zoneBlackValid=TRUE Confirm that the signals can be seen and are consistent between PhasorPoint and ADMS. Confirm that ADMS GTC for Network Initialisation is only enabled if zoneBlack=TRUE.	☑
Comments	Identification of a system black event from the DRZC is working without errors.	

Outcome ☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Test 1.01	Zone Black identification from ADMS	
Set-up	Configure the OPAL-RT model with no generation running, no load and all zero voltages. Circuit breaker positions are configured typically for a post-blackout condition – most network circuit breakers closed, most generator circuit breakers open, with some exceptions. PMU data is valid. RTU data is zero volts at all 33kV and 11kV measurements. PMU data is valid and zero volts.	
1. Procedure	Zone black confirmation – RTUs - normal. Inspect the Zone Black status determined by ADMS.	
2. Verification	Zone black digital status value from RTUs is TRUE in ADMS. Confirm that the overall logical combination of the DRZC zoneBlack and ADMS zone black is also TRUE. ADMS GTC Network Initialisation status should be Ready.	☑
3. Procedure	Zone black confirmation – RTUs - exceptions. A series of test conditions to prove the cases of detecting non-zone-black conditions. After each condition, return to the default set-up case. To create a valid non-zero critical measurement, energise the HV and LV sides of the 132/33 transformer. All 33kV line breakers open. Inspect the GTC status for Network Initialisation to check if status is Ready or Not Ready.	
4. Verification	Confirm that both the ADMS RTU-based measure and DRZC based measure of zoneBlack are Zone Black=FALSE. Confirm that the signals can be seen and are consistent between PhasorPoint and ADMS. Confirm that ADMS GTC for Network Initialisation is Not Ready	☑
Comments	Confirmation of Zone black from ADMS is working without errors.	

Outcome ☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Test 1.02	Group Tele-Control for Network Initialisation	
Set-up	Configure the OPAL-RT model with no generation running, no load and all zero voltages. Circuit breaker positions are configured typically for a post-blackout condition – most network circuit breakers closed, most generator circuit breakers open, with some exceptions. PMU and RTU data are valid and zero volts.	
1. Procedure	Confirm zoneBlack signal is set Confirm GTC Network Initialisation is Ready Confirm normal function of GTC Network Initialisation - select and run GTC Network Initialisation from ADMS dashboard shortcut.	
2. Verification	Confirm in Dashboard “Completed no errors” Confirm in GTC log that all actions have completed. Confirm on simulated network that breaker states have been changed as specified in the GTC command list.	☑
3. Procedure	Confirm exception function of GTC Network Initialisation Create condition where at least two breaker state changes to not respond Select and run GTC Network Initialisation from ADMS dashboard shortcut	
4. Verification	GTC Network Initialisation should return “Completed with errors” Examine consistency between the network states, GTC schedule and the errors reported in the GTC log.	☑
Comments	Network initialisation is proven and working. GTC log reports Completed when no errors occur. Errors appear in the GTC log as below when breakers opening fails. GTC log reports Completed when no errors.	



Favourites (5 displayed)

Reference	Class	Name	Status	Last Command	Last Command Time	Executed By	Execution Pattern	Plan Name	Description	Parent Group	Broadcast
GTC-27-A	Default GTC	BDR PreRestoration Steps	Error	Execute	04/02/22 13:37:16	SYSTEM	Linear				No
GTC-28-A	Default GTC	BDR Restoration Steps Initial Ve	Created	Execute	20/12/21 16:44:26	Andrei Strugariu	Linear				Yes
GTC-29-A	Default GTC	BDR Initialise Balancing	Completed	EXECUTE_ON	04/02/22 11:54:44	SYSTEM	Linear				No
GTC-43-A	Default Load Shed	BDR Priming Request	Ready	EXECUTE_ON	20/01/22 14:49:13	Andrei Strugariu	Linear				No
GTC-44-A	Default Load Shed	BDR Initialize Network	Completed	EXECUTE	04/02/22 11:58:05	SYSTEM	Linear				No

GTC-27-A : BDR PreRestoration Steps - Error

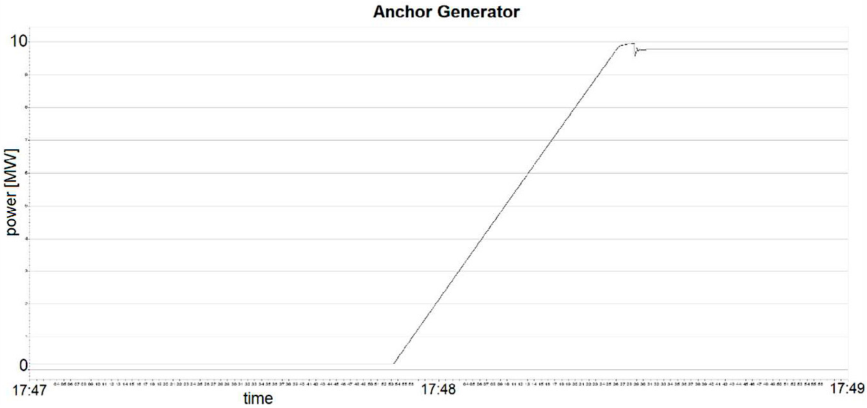
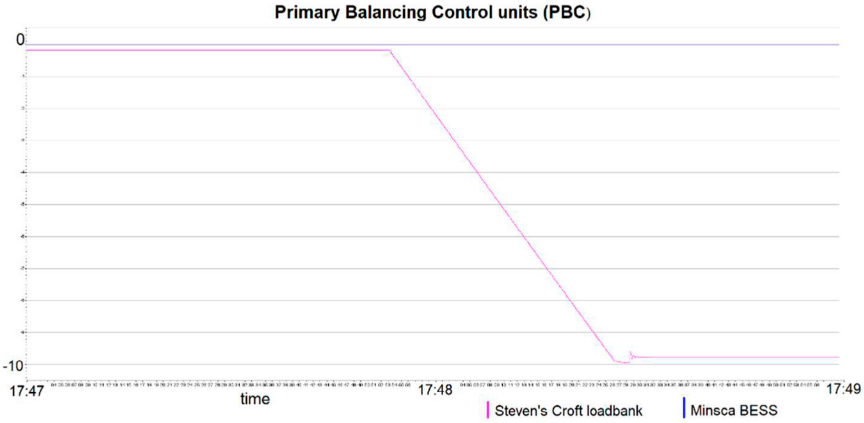
Step	Reference	Comment	Description	State	Status	...		...
1	15213165U		CHAPELCROSS GSP Grid S/S, PS21/217 LANGHOLM 33KV T GRETNA 33KV CB	OPEN	Completed	...	✓	
2	15213169U		CHAPELCROSS GSP Grid S/S, MINSCA 33KV CB	OPEN	Completed	...	✓	
3	15213157U		CHAPELCROSS GSP Grid S/S, MIDDLEBIE 33KV SW/STN CB	DBI-00	🟥 Error	...	✓	
4	15213153U		CHAPELCROSS GSP Grid S/S, ANNAN T1 CB	DBI-00	Ready	...	✓	
5	15213156U		CHAPELCROSS GSP Grid S/S, LOCKERBIE 33KV RT9A T CARRUTHERSTOWN 33KV CB	DBI-00	Ready	...	✓	
6	15213157U		CHAPELCROSS GSP Grid S/S, MIDDLEBIE 33KV SW/STN CB	DBI-00	Ready	...	✓	
7	15213158U		CHAPELCROSS GSP Grid S/S, GRETNA NO2 (RT 1A) CB	DBI-00	Ready	...	✓	
8	15213162U		CHAPELCROSS GSP Grid S/S, BUS SECTION TELE CB NI	DBI-00	Ready	...	✓	

Figure 5 Network Initialisation GTC error log

Outcome ☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Test 1.03	Observation of anchor startup with ADMS and PhasorPoint
Set-up	Start with the OPAL-RT model in the condition at the end of the previous test where the network initialisation is complete. The anchor generator should be energised and running in no-load condition. The generator ready to ramp up for the test, balanced by the load bank. The ADMS and PhasorPoint should initially show voltage at the point of connection but no power. PhasorPoint should initially show the anchor power and load bank power on a MyViews page relative to the limits for normal operation. **Revision:** It was originally planned that PhasorPoint should create an alert (amber) when the anchor was not ready. However, Anchor Ready cannot be reliably determined from data alone and an automated power-based decision could be misleading. Instead, the operator will receive a call from the anchor personnel and revise the dashboard status accordingly.
1. Procedure	Start ramping up anchor generator, keeping in balance with the load bank.

	Revision: Confirm using PhasorPoint that anchor ramp is observed and reaches desired level. (There is no PhasorPoint Anchor Ready signal to be confirmed.)	
2. Verification	PhasorPoint and ADMS should show that volts are applied at the generator. PhasorPoint should show growing power values for the anchor and load bank in MyViews page as the generator is ramped up and load bank is increased.	☐
3. Procedure	Bring anchor generator and load bank into the normal operating zones between the trimMargin +/- limits. Do not induce poorly damped oscillations, but if they appear spontaneously PhasorPoint should show them.	
4. Verification	Observe power flow in anchor generator in PhasorPoint MyView page. Original test assumed anchor power should rise from zero until it exceeds the trimMargin- limit. Load bank power should start at zero and drop down to a negative value below the trimMargin+ limit. However, this was not possible with the configuration and limits used. Confirm consistency in P&Q values in PhasorPoint and ADMS.	☐
Comments	Since ramping up the anchor generator will be performed by personnel on site, and communication of "Anchor Ready" will happen via phone call. The original plan to include an "Anchor Ready" signal in PhasorPoint was not done since it is not possible to confirm from measurements alone whether the anchor is ready. Due to a difference in the magnitude of Trim limits, it is not possible to have the anchor generator above its low red area (P>20MW), considering that the loadbank capacity is only -15MW. The condition in Step 4 cannot be achieved with the given configuration because the load bank capacity is not sufficient for the generator to operate with the intended control margin. A compromise is found with the ramp up ending at about 10MW, as shown in the pictures below, while the Slow Balancing will allow the anchor generation to increase as soon as more loads are added to the network during the restoration process.	

	 Figure 6 Anchor Generator ramping up  Figure 7 Loadbank ramping down	

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

4.3 Island Balancing and Load Pickup

Once the anchor generator is available and operating with the load bank at a stable and sustainable power level, the network can be energised and loads picked up sequentially.

Test 2.00	**Starting and stopping Fast and Slow Balancing from ADMS**	
Set-up	The anchor generator and load bank are within normal limits and the Anchor Ready state is reached, as at the end of the previous test.	
1. Procedure	Use the ADMS main DRZ display to select the Fast Balancing Start and Slow Balancing Start commands.	
2. Verification	Use PhasorController Designer to confirm that Fast and Slow Balancing have been enabled. Confirm in PhasorPoint that the relevant digitals have been received, indicating that balancing action is enabled.	☑
3. Procedure	Use the ADMS main DRZ display to select the Stop Fast Balancing and Stop Slow Balancing commands.	
4. Verification	Use PhasorController Designer to confirm that Fast and Slow Balancing have been suspended. Confirm in PhasorPoint that the relevant digitals have been received, indicating that balancing action is suspended.	☑
5. Restore	Restart fast and slow balancing to continue to next test.	☑
Comments	Completed without errors. ADMS controls the start-up of DRZC processes by operator-initiated selection from the dashboard.	

Outcome ☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Test 2.01	Energising the GSP 33kV side	
Set-up	The anchor generator and load bank are within normal limits, as at the end of the previous test. Fast and Slow Balancing are enabled. Process is now entering Stage 3.	
1. Procedure	Initiate a switching sequence to energise the line from the anchor generator to the GSP 33kV bus, including all sections. At this stage, the line and substation are energised, and no loads are picked up. **Revision:** Further to guidance from the Distributed Restart project team, the network is also energised at this stage to the 33kV windfarms to allow them to prepare to start. They initially start as small loads and wait for an appropriate signal from the DRZC before starting to generate.	
2. Verification	Using the ADMS network display, confirm closure of breakers and voltage applied at buses. In PhasorPoint, observe the transients in voltage as the network is energised. Confirm that no Fast or Slow Balancing actions were taken.	☑
Comment	Completed without errors. In early trials, the 33kV windfarms were modelled to start generating after a pre-defined time from energisation. However, the minimum generation level resulted in too much generation in the island before load pickup started. It was therefore agreed that there should be a stage where DRZC signals readiness for the 33kV windfarms to start generating. This resolved the generation excess.	

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

Test 2.02	Simple load pickup and trip events – fast balancing	
Set-up	The anchor generator and load bank are within normal limits. Fast and Slow Balancing are enabled. Stage is 3. This is the condition reached at the end of the last test. Some preliminary tests of the network model are required using the model to determine suitable values for the parameters described in Appendix A for defining the load pickup capacity. These values will be entered into the resource configuration table and the DRZC will provide a value for the load pickup capability in the current conditions (without priming). Thresholds for triggering Fast Balancing are set in advance, such that it takes action on events that exceed the ROCOF limit or that would cross the frequency level limit if fast balancing action were not taken. This depends on the island's inertia and speed of PR governor response.	
1. Procedure	Initiate a simple load pickup event manually from ADMS, i.e., not using the ADMS automation. Load pickup should be sufficiently large to trigger fast balancing. Fast balancing should produce a trigger and initiate a load bank demand reduction of similar size to load pickup.	
2. Verification	Confirm that fast balancing event is triggered in PhasorPoint using the archive data. Confirm the MW value of load bank change in PhasorPoint and check consistency with load pickup. Using PhasorPoint, confirm that frequency is stabilised such that |RoCoF| does not exceed 0.8Hz/s for more than 0.5s and frequency remains above 48.6Hz. Confirm using PhasorPoint that Fast Balancing Available signal is restored, indicating that the system is ready to respond to another disturbance.	☑
3. Procedure	Trip the same load. Fast balancing should produce a trigger an initiate a load bank demand increase of similar size to the load trip.	
4. Verification	Confirm the Fast Balancing action as above, except that the action on the load bank is in the opposite direction (demand decrease).	☑
5. Procedure	Repeat above steps with smaller disturbances to confirm that a suitable event threshold has been configured for Fast Balancing.	
6. Verification	Confirm action as above, and review the frequency behaviour using events close to the trigger threshold level. Confirm that events with no trigger stay within the allowed frequency and ROCOF limits. Also confirm that the events where a Fast Balancing trigger is applied keeps frequency within limits and provides a proportionate response. If not, then revise thresholds and repeat.	☑

7. Comments	Acceptable results are achieved by setting a RoCoF trigger threshold at ±0.25 Hz/s. System's behaviour for a -16MW cold load (-11MW steady state) is depicted in Figure 8. The initial value of the load after the pickup is less than what is estimated by the DRZC as pickup capability of the system without priming; frequency and RoCoF are supposed to remain within acceptable thresholds for the whole duration of the event. During the pickup event, the frequency reached a minimum of 48.6Hz, while the RoCoF stayed under -0.8Hz/s for 0.060s, and under -1.0Hz/s for 0.028s. This is acceptable since ROCOF relay tripping requires ROCOF outside +/-1Hz/s for 0.5s. After the event, the anchor unit generation stabilised 5.5MW above the operating point before the event, while the remaining additional power is shared among PBC unit (loadbank increases from -9MW to -5.5MW, and BESS from -2.5MW to 2.5MW). Then, the setpoints of PBC units remain stable, while the PR's droop causes its generation to decrease gradually, following the behaviour of the load. When the load dropped, its value was -11.5MW. The frequency peaks at 50.9Hz, the RoCoF never exceeds 0.6Hz/s. After the event, the anchor generator operating point is 9MW lower than before the event, and the remaining power difference is shared between the PBC units. The drop in generation of the anchor then triggers a Slow Balancing action, aimed at bringing the PR unit above 20MW.	

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

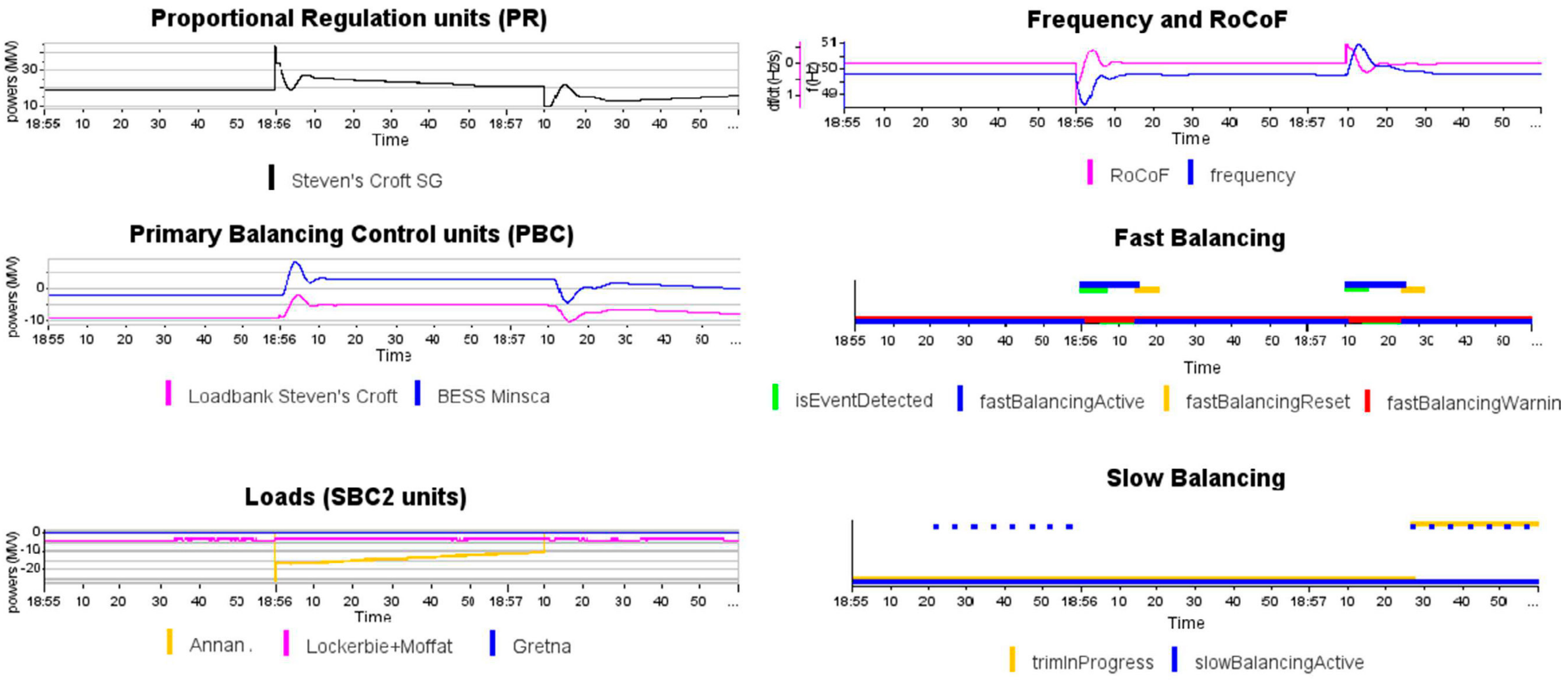
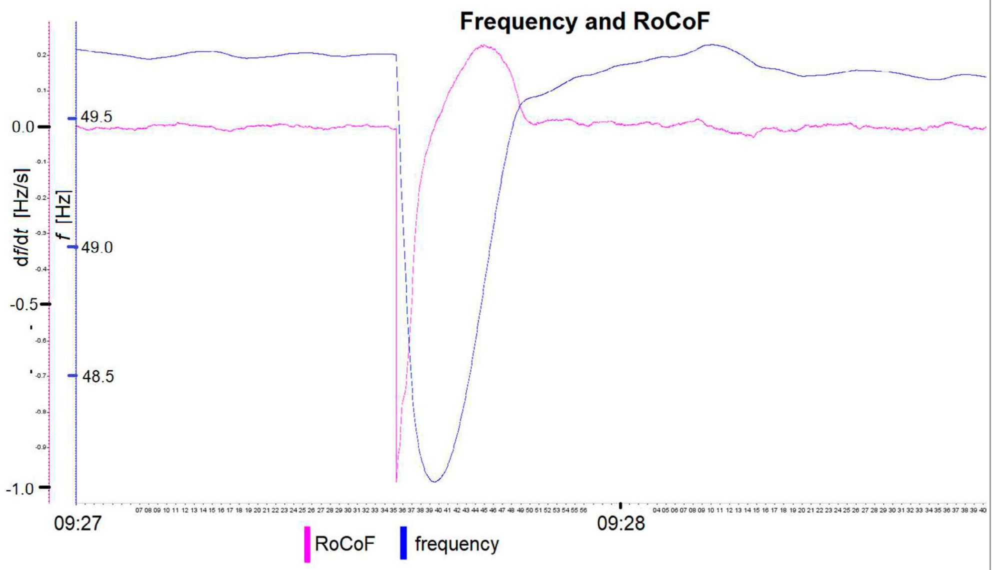
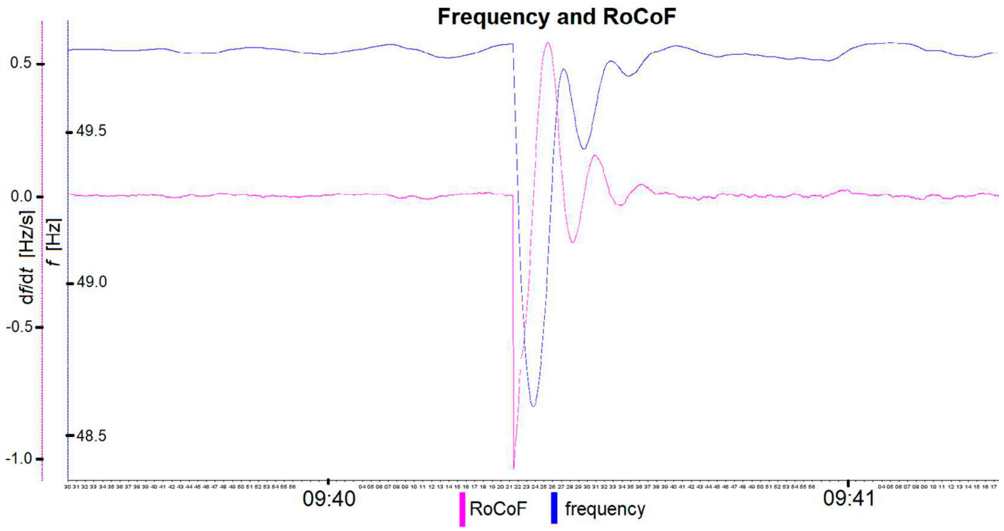


Figure 8 Fast Balancing action after a load pickup and load drop.

Test 2.03	Large load pickup with priming	
Set-up	The anchor generator and load bank are within normal limits. Fast and Slow Balancing are enabled. Stage is 3. Ewe Hill and Solwaybank windfarms are running at low output, with wind resource available to full capacity. Thus, SBC1 capacity is available. PBC capacity is limited to the Stevens Croft load bank only. Load pickup capability is calculated by DRZC with and without priming. Set Annan or Lockerbie load pickup (which is 1.5xsteady-state value) to a value larger than the currently available load pickup capacity but less than the pickup capacity with priming. An automated procedure is configured in ADMS to pick up the load. See Figure 11 for base case condition and intended action of priming.	
1. Procedure	DRZC sends the current pickup capacity and pickup capacity with priming to ADMS. ADMS checks the expected load pickup from connecting the primary. Comparing with the pickup capacity values, ADMS confirms that priming is required. ADMS commands DRZC to carry out the priming function. DRZC then selects the appropriate value of SBC1 power to dispatch, balanced by adjustment of PBC to maximise the pickup capacity. Once priming is complete and SBC1 and PBC have reached their targets, DRZC revises the pickup capacity values sent to ADMS. A “priming ready” signal is sent from DRZC to ADMS. ADMS confirms load is within the current pickup capacity and picks up the load. Fast balancing is triggered by DRZC.	
2. Verification	Confirm that the above sequence has been carried out successfully from the ADMS logs. Confirm using PhasorPoint and/or ADMS that PBC response is similar to the load pickup value, or its maximum response. Confirm using PhasorPoint that ROCOF and frequency level remain within their respective limits throughout the process. Confirm that fast and slow balancing return to normal state after the actions are complete.	☑
3. Procedure	Restore to the original state and repeat the test with manual load pickup.	
4. Verification	Confirm from PhasorPoint that the ROCOF and/or frequency level violates the thresholds. This confirms that the priming function tested above is required for the load pickup event.	☑
5. Procedure	Restore to the original state and set load pickup value to be larger than the pickup capacity with priming.	

6. Verification	Confirm that the ADMS reports "completed with errors" and the load pickup is not carried out. The operator is made aware of the failure to pick up the load.	☑
7. Procedure	Investigate case where expected load pickup is large, requiring priming, but actual load pickup is significantly smaller.	
8. Verification	Confirm that priming is carried out, but PBC responds to the actual size of load pickup. Once normal fast and slow balancing resume, there may be another readjustment of the resources.	☑
9. Procedure	Investigate case where expected load pickup is small, not requiring priming, but actual load pickup is significantly larger and requires priming.	
10. Verification	Confirm that priming is NOT carried out; PBC responds to its maximum capacity, but this is insufficient, and frequency exceeds its limits. Note that this case is not expected in reality – estimates of load pickup should be conservative.	☑
Comments	The priming call GTC from the ADMS is effective. Priming function allows frequency and RoCoF to stay within acceptable thresholds. Below, frequency and RoCoF behaviour is shown for picking up a load (-20MW cold start, -14MW steady-state). Without priming, the frequency drops to 48.1 Hz and RoCoF drops below -1Hz/s (RoCoF below -0.8Hz/s for 1.2s). After priming the network, the same load pickup results in a minimum frequency value of 48.6 Hz and RoCoF of -1.0Hz/s for much less than 0.5s (RoCoF below -0.8Hz/s for 0.35s).  Figure 9 Frequency (blue) and RoCoF (magenta) behaviour after a -20MW load pickup, WITHOUT PRIMING. Minimum frequency value = 48.1 Hz; Minimum RoCoF = -1.0Hz/s.	

	 Figure 10 Frequency (blue) and RoCoF (magenta) behaviour following a -20MWW load pickup, WITH PRIMING. Minimum frequency value = 48.6 Hz; Minimum RoCoF = -1.0Hz/s. During test steps 9/10 when the estimated value for the load was intentionally set too low and the priming function was not activated by the energising automation process, frequency and RoCoF exceeded pre-set limits.

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

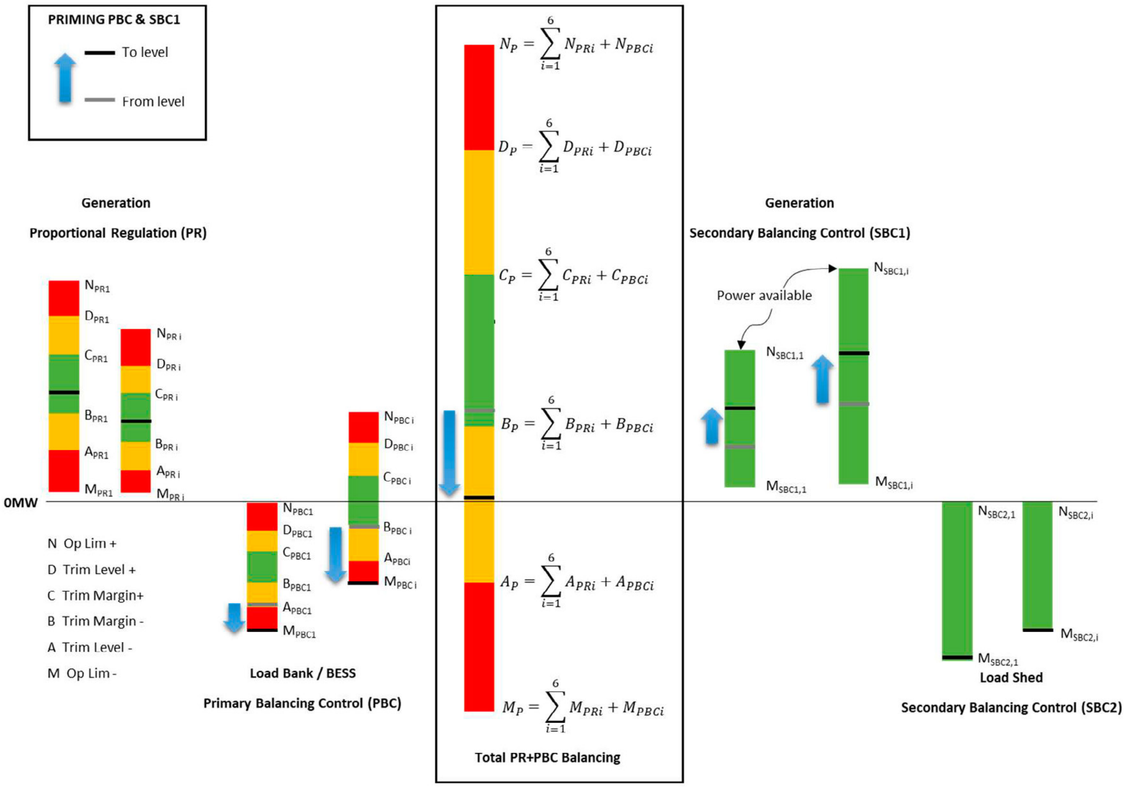


Figure 11 Priming process using SBC1 to bias PBC resource for maximum load pickup

Test 2.04	Energising circuits with balancing resources and expanding DRZC controllable resources	
Set-up	The anchor generator and load bank are at mid-range within normal limits. Fast and Slow Balancing are enabled. 33kV network is energised to Chapelcross busbars, but load is not yet picked up. Table of resources is populated, but the only available resources are one PR device (the anchor generator) and one PBC (the load bank at the anchor generator). Other resources are not active. The network is ready to pick up loads and renewable generation. Annan and Lockerbie should be at high load values, so that Lockerbie pickup initiates Slow Balancing and SBC1 deployment. Power available signal is provided at DERs. The following values are observed in ADMS in real time: Load pickup (& gen loss) capability now Load pickup capability with priming Load loss capability now Proportional Regulation sum of power and limits Primary Balancing Control sum of power and limits Secondary Balancing Control (1) sum of power and limits Secondary Balancing Control (2) sum of power and limits Individual values for all PR, PBC, SBC1, SBC2 (dynamic if appropriate) for Op Limit + / - Trim Level +/- Trim Margin +/- Measured power Connected _Active (status)	
1. Procedure	Energise Solwaybank windfarm and start the Solwaybank windfarm generation. Ramp up Solwaybank power in OPAL-RT until Activate_Margin is reached and "Connected_Active" state is raised.	
2. Verification	Confirm using PhasorPoint that generation has been added. Frequency should rise and PR output drop. Confirm using PhasorController Designer that the corresponding SBC1 entry in the Resource Table becomes active. Confirm in ADMS that the levels shown for the Solwaybank windfarm are consistent with Power_Available, the Measured Power is correct and the Connected_Active state is raised.	☑

	Confirm in ADMS that the SBC1 sum of power and limits has changed to reflect inclusion of the windfarm.	
3. Procedure	Initiate Annan load pickup using automation script. Steady-state load level should be greater than "Activate_Margin"; the actual load should be 1.5x steady state and ramp down over time to 1x steady-state. Since Annan is counted as an SBC2 resource, it should be observed in the Resource Table as an active SBC2, provided the Measured Power is greater than the Activate Margin. Depending on the Fast Balancing thresholds and impact of the load pickup, Fast Balancing may be activated, possibly followed by Slow Balancing.	
4. Verification	Using PhasorPoint, confirm the load pickup and confirm that the PR and PBC values stay or return within the Trim Level limits. Using ADMS, confirm that the load at Annan is recorded as SBC2 resource.	☑
5. Procedure	Energise Minsca windfarm and BESS. Start the Minsca windfarm generation. Ramp up Minsca power in OPAL-RT until Activate_Margin is reached and "Connected_Active" state is raised. Change BESS power by small amount. DRZC adds the windfarm as SBC1 resource and BESS as PBC, with both being identified as "Connected_Active"	
6. Verification	Confirm using PhasorPoint that generation has been added. Frequency should rise and PR output drop as windfarm is ramped up. Show that BESS power change is observable. Confirm using PhasorController Designer that the corresponding SBC1 and PBC entries in the Resource Table becomes active. Confirm in ADMS that the levels shown for the Minsca windfarm and BESS are consistent with Power_Available, the Measured Power is correct and the Connected_Active state is raised. Confirm in ADMS that the sum of PBC and SBC1 power, available power and levels change correctly.	☑
7. Procedure	Repeat stage 1 above for Ewe Hill windfarm.	
8. Verification	Repeat stage 2 above for Ewe Hill windfarm.	☑
9. Procedure	Repeat stage 3 above to pick up Lockerbie load (without Kirkbank and Moffat). DRZC should initiate Fast and Slow Balancing, including use of SBC1 resource.	
10. Verification	Repeat stage 4 above, confirming that Lockerbie load is added to SBC2.	☑
11. Procedure	Continue to full energisation of all loads and DERS. DRZC may activate Fast and Slow Balancing actions.	

12. Verification	Confirm that PR and PBC continue to act as load is picked up	☑
Comments	SBC1 and SBC2 resources are correctly shown in the ADMS interface. Windfarms initially behave as loads. When their initial transients are over, they send to the DRZC a "windfarm ready" signal, together with the estimate available power for generation. After receiving the estimate generation threshold and "windfarm ready", the corresponding SBC1 unit is considered "in use" by the DRZC. This is observable in the ADMS through changes in Low and High Margins for SBC1 units.	

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Test 2.05	Variations of DER and load power causing regulation and slow balancing actions	
Set-up	This test is to demonstrate the slow balancing functions as described in the cases in Figure 12 through Figure 26 below. The network is set up initially as in Figure 12 Base Case with all resources within the Trim Margins. Frequency should be near 50Hz. SBC1 should have margin to adjust in both directions. The test cases are applied by adjusting the controlled units to the required pre-balancing conditions, balanced by changing loads in OPAL-RT.	
1. Procedure <u>Case 1a</u>	Tests for adjustment of PR and PBC in high frequency case without SBC1. Adjust PBC to positions shown in Figure 12, adjusting load to balance. Reduce load gradually and frequency increases. Observe PR approaching Trim Limit. Continue until PR reaches trim limit and triggers the slow balancing action. DRZC Slow balancing then triggers adjustment of PBC to decrease power to the island. Frequency reduces in response to PBC decrease, causing PR to shift close to Trim Margin.	
2. Verification	Confirm that the above sequence has been carried out successfully using PhasorPoint. Confirm that PR is restored to within Trim Margins (or close) Confirm that adjustment is balanced between PBC resources Confirm that none of the resultant values are outside Trim Limits. Confirm that frequency stays close to 50Hz (+/- 0.2Hz) Confirm that ADMS has logged the changes and updated resource values.	☑
3. Procedure <u>Case 1b</u>	Test for adjustment of PR and PBC requiring use of SBC1 since using only PBC would cause a PBC Trim Level violation. Adjust PBC to load points shown in Figure 13, balancing with load and keeping frequency close to 50Hz. Reduce load to increase frequency gradually, causing PR to reduce until it reaches the Trim Level. DRZC will detect that adjusting PBC would cause a PBC Trim Level violation, therefore applies the power change at one or more SBC1 resource.	
4. Verification	Confirm using PhasorPoint that the Trim Level violation is resolved and PR returns to Trim Margin, or close. Confirm that SBC1 control has been applied in place of the PBC(s) that would reach the Trim Level. Confirm that frequency is restored close to 50Hz. Confirm that ADMS has logged the changes and updated resource values.	☑

5. Procedure Case 1c	Test for PBC reaching Trim Level, resolved by SBC1 control, as adjusting PBC would cause PR to reach Trim Margin. For PBC to reach the Trim Margin requires a Fast Balancing action. Arrange PBC and PR to be near the lower Trim Levels with above nominal frequency. Introduce a load trip to create a Fast Balancing response. This results in one or more PBC crossing the Trim Level. DRZC Slow Balancing detects that restoring PBC within Trim Margin would cause PR to violate the Trim Margin. Reduction in SBC1 is applied together with increase in the PBC resource(s) that crossed Trim Level.	
6. Verification	Confirm using PhasorPoint that the levels return within Trim Level and the unit that crossed the Trim Level has been restored to the Trim Margin. Confirm that frequency is close to 50Hz. Confirm that PBC and SBC1 adjustments are balanced. Confirm that ADMS has logged the changes and updated resource values.	☑
7. Procedure Case 2	In this case the total PR+PBC balancing reaches its lower limit, indicating that there is insufficient total high frequency / power reduction margin. One or more PR or PBC resources must also have crossed the Trim Level. In this case, SBC1 must be used to resolve the violation. The target in this case is to provide an SBC1 response that will restore PR+PBC to the Trim Margin level, or as close to it as possible given the available SBC response. Ensure that there is a total SBC1 response that is close to (but slightly less than) the difference between PR+PBC Trim Level and Trim Margin, as shown in Figure 15. Adjust PBC levels close to the Trim Levels, keeping within the limit and balancing PBC with load change. Gradually reduce load to increase frequency, causing PR to lower and cross the Trim Level. A small load trip may be used to ensure that the PR+PBC margin is reached. DRZC Slow Balancing dispatches SBC1 resource to the smaller of the total available SBC1 or the distance to the PR+PBC Trim Margin. PR restores to within its Trim Margins, and DRZC estimates the amount of additional response to use for redispatching PBC to (or closer to) its Trim Margins.	
8. Verification	Use PhasorPoint to confirm that SBC1 resource has been used, PR is restored to Trim Margins and PBC restored close to Trim Margins. Frequency should be close to 50Hz. Confirm that ADMS has logged the changes and updated resource values.	☑
9. Procedure Case 3	Frequency is low and PR reaches its upper Trim Limit, resolved by balancing with PBC, without requiring SBC1. With PBC close to mid-range, increase loads so that frequency decreases and PR balances the increased load. Continue gradually increasing load until PR reaches the Trim Limit.	

	DRZC detects PR Trim Limit violation and increases PBC setpoints (within Trim Levels). Increase in power causes frequency to rise close to 50Hz, and PR reduces to around Trim Margin level.	
10. Verification	Use PhasorPoint to confirm that PBC is activated to restore frequency to near 50Hz and PR restored to around Trim Margin. Confirm that PBC remains within Trim Levels. Confirm that SBC1 is not used. Confirm that ADMS has logged the changes and updated resource values.	☑
10. Procedure Case 4.a	Frequency is low and the total {PR+PBC} exceeds the upper trim limit (Figure 23). Set SBC1 resources to mid-range so that there is capability to dispatch up or down. Set PBC very close to the high Trim Level. Increase load so that frequency decreases and PR balances the island by increasing output. Continue increasing load until PBC reaches upper Trim Limit at the same time as {PR+PBC} reaches its limit. DRZC slow balancing will increase SBC1 so that {PR+PBC} reduces to the Trim Margin or the limit of SBC1 capacity. Total PBC is reduced by an amount that allows PR to reach the Trim Margin level.	
11. Verification	Using PhasorPoint, confirm that PR resources are restored to around the Trim Margin+ level and PBC is restored below the Trim Level. Confirm that SBC1 is used to the appropriate level. Confirm that total {PR+PBC} returns to around the Trim Margin level, or as close as possible with the available SBC1 resources. Confirm that ADMS has logged the changes and updated resource values.	☑
12. Procedure Case 4.b	Variant of 4.a where Fast Balancing event results in the total {PR+PBC} exceeds the upper trim limit. It is more likely to reach a total {PR+PBC} Trim Limit following an event than through slow drift (Figure 25). Set SBC1 resources near mid-range so that there is capability to dispatch up or down. Set PR and PBC close to the high Trim Levels through adjusting load and PBC such that PR output is between the Trim Limit and Trim Margin. Manually apply a load pickup event large enough to trigger Fast Balancing and cause {PR+PBC} to exceed Trim Level. Fast Balancing response leads to PBC response to upper operating limit. PR also increases above Trim Level. Total {PR+PBC} increases above Trim Level. DRZC slow balancing increases SBC1 to reduce {PR+PBC} to its Trim Margin, or may be limited by the SBC1 capacity. Total PBC is reduced by an amount that allows PR to reach the Trim Margin level.	

11. Verification	Using PhasorPoint, confirm that load pickup and fast balancing have operated as expected, and total {PR+PBC} exceeds the Trim Level. At next Slow Balancing cycle, confirm that SBC1 is deployed to its maximum (or sufficient to reduce {PR+PBC} to Trim Margin). Confirm that PR reduces to around Trim Margin or below. Confirm that PBC reduces below the Trim Level. If SBC1 resource is sufficient, PBC should reduce to Trim Margin. Confirm that total {PR+PBC} returns to around the Trim Margin level, or as close as possible with the available SBC1 resources. Confirm that ADMS has logged the changes and updated resource values.	☑
Comments	Slow Balancing is effective in maintaining PR and PBC units within A and D thresholds, whenever there are enough resources available for trimming. In cases where there are insufficient resources, Slow Balancing still activates every 5s, but if no change in setpoints is sent to units e.g. due to lack of resource, trimInProgress is not raised. More comments below, with relevant illustrations.	

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

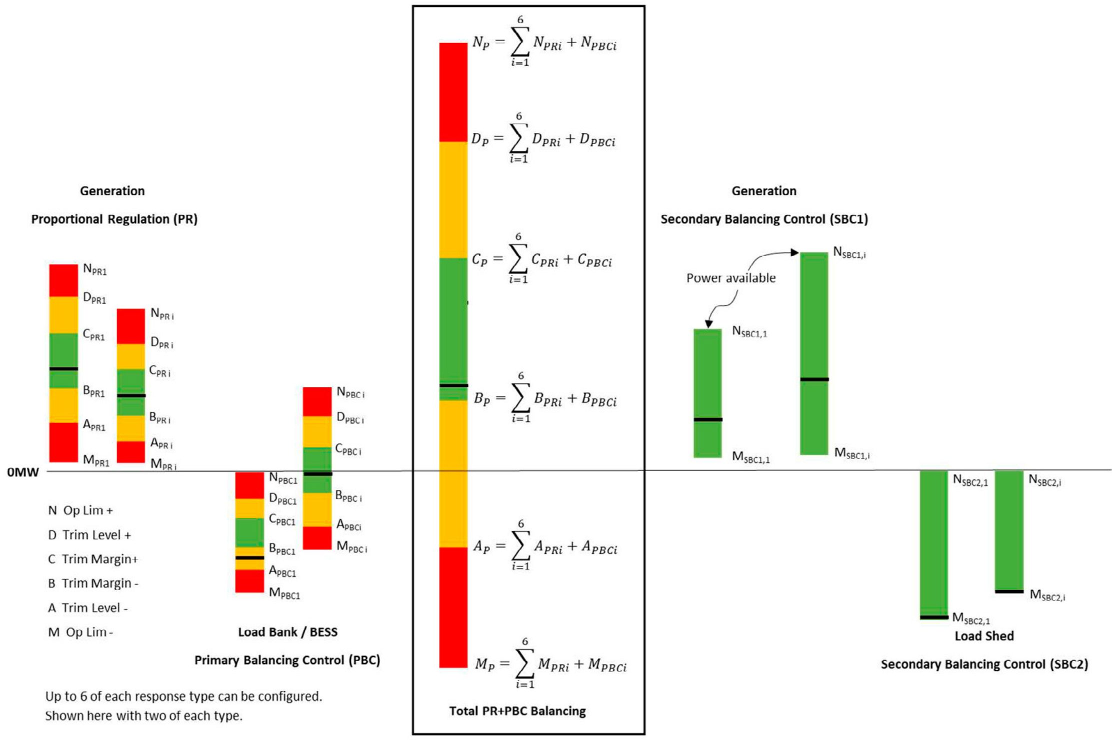


Figure 12 Base Case High Frequency/Excess power; PR+PBC is within Trim Limits {Ap, Dp}.

In **Case 1.a**, frequency is high, causing PR output to be low due to governor control. In Case 1.a there is margin for PBC resources to reduce without reaching A_{PBC} limits. Also, the total of PR+PBC is within limits A and D, so no trigger for SBC resources.

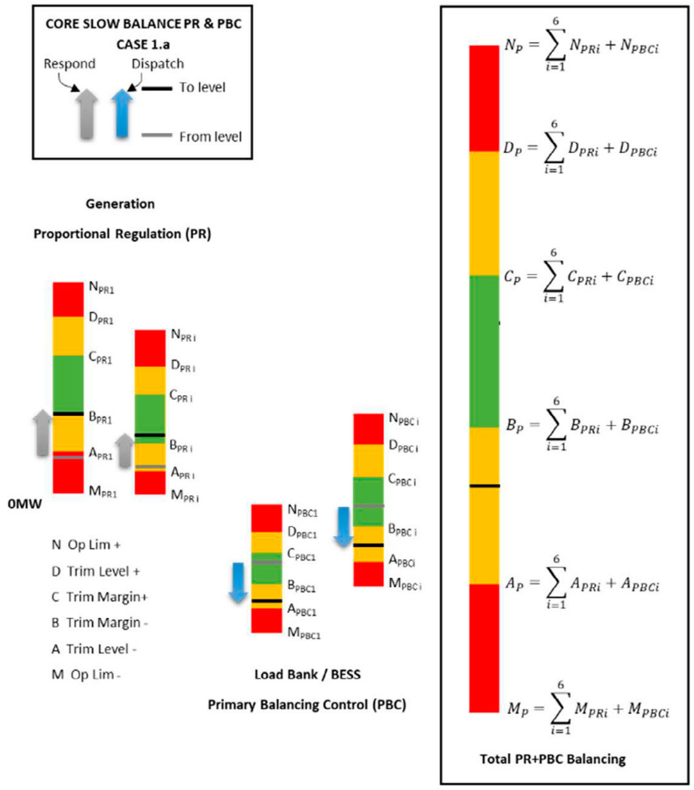


Figure 13 Case 1.a: High Frequency, PR resolved by PBC adjustment

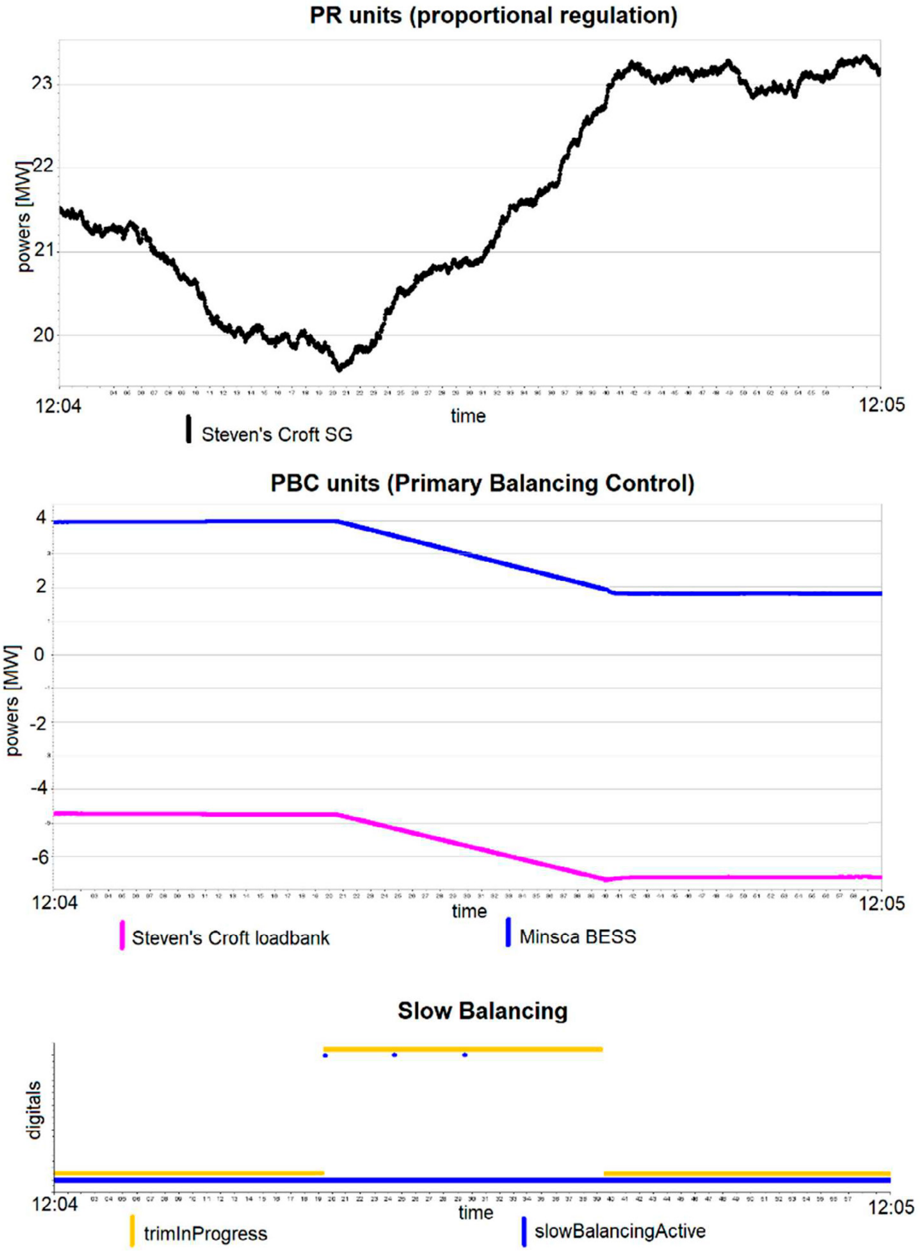


Figure 14 Slow Balancing action, case 1.a

Slow Balancing function performs a check on the power level of PR and PBC units every 5s. When the anchor generator crosses 20MW axis, corresponding to its A threshold, Slow Balancing is triggered, and new setpoints are sent to PBC units. PBC powers decrease gradually in ramps, in order to prevent a RoCoF event that would trigger a Fast Balancing action. The system stabilises with both PBC units in the green area, while PR is 1.5MW below its B threshold, but above A, which is the intended outcome.

In **Case 1.b**, the balancing action to resolve PR would cause a PBC resource to drop below the A_{PBC} limit, so the scheme will use SBC1 resource in place of the PBC resource that would be below the limit.

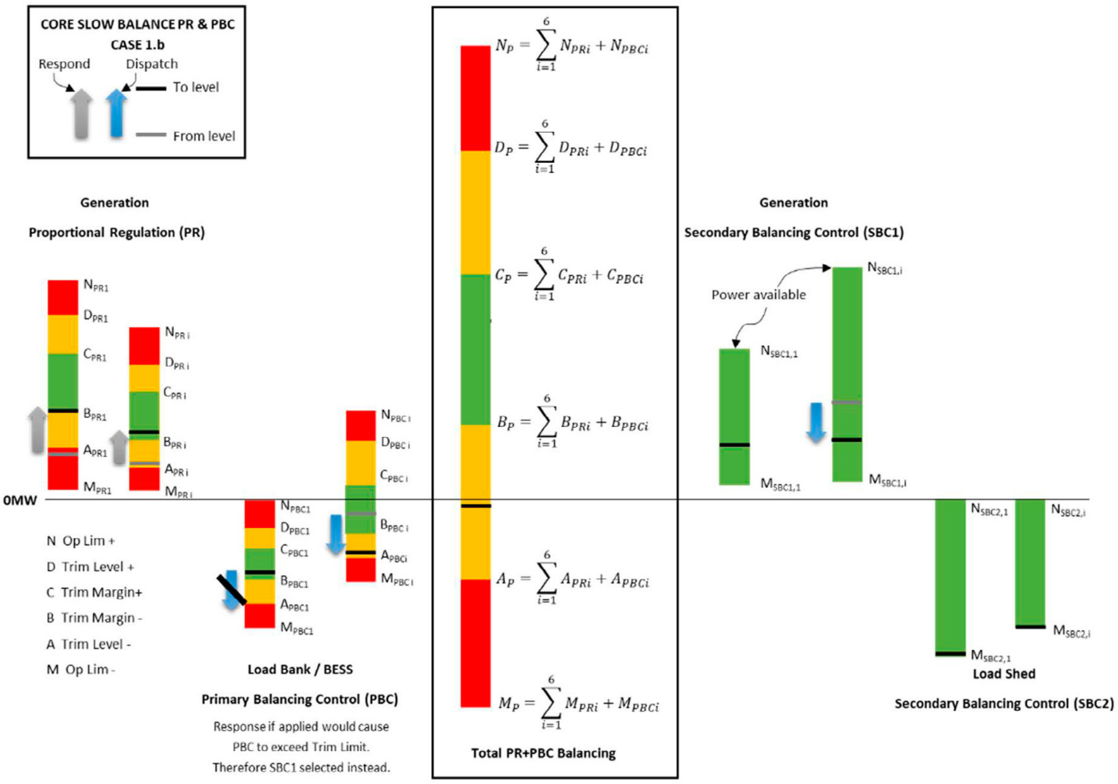
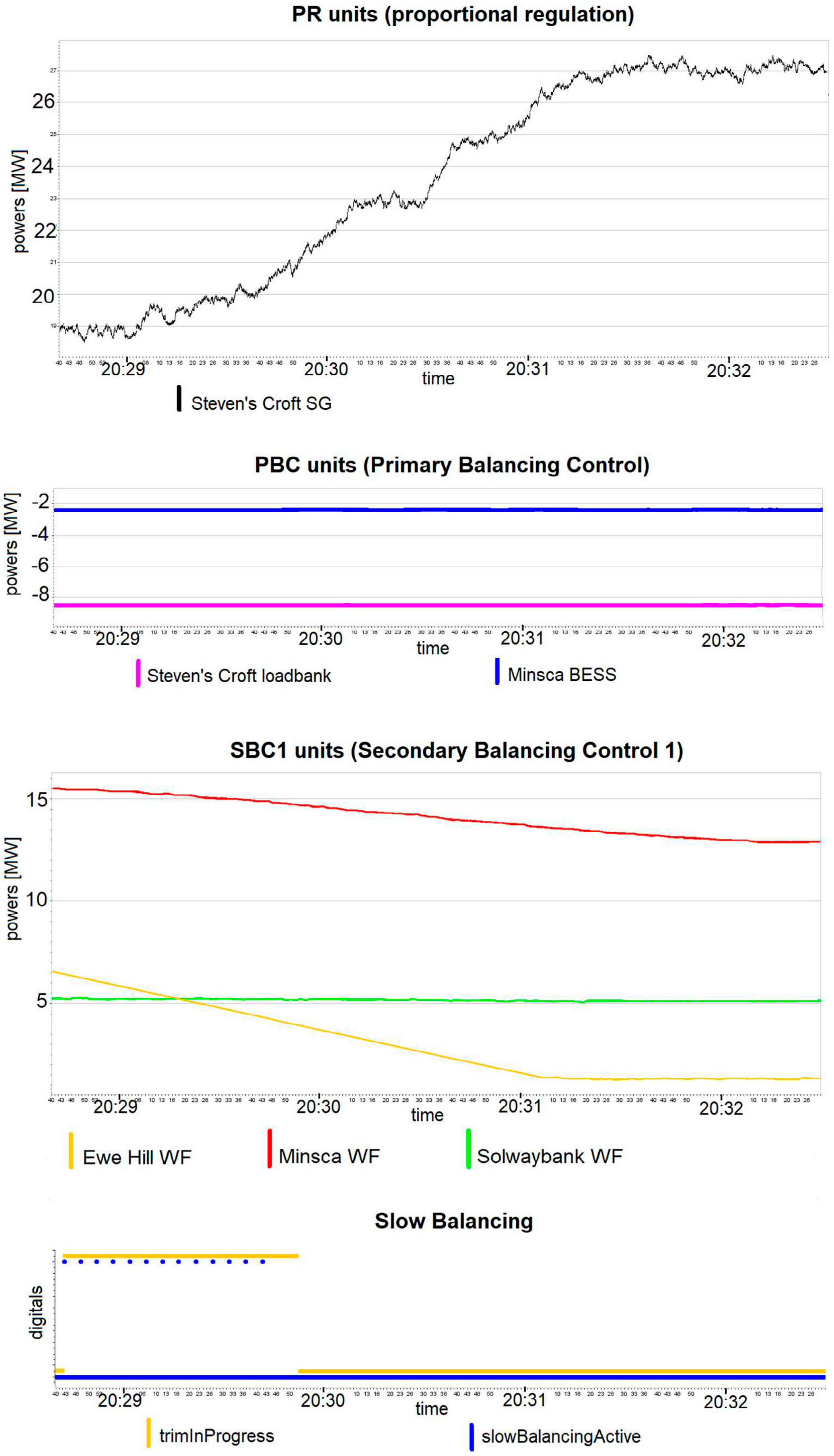


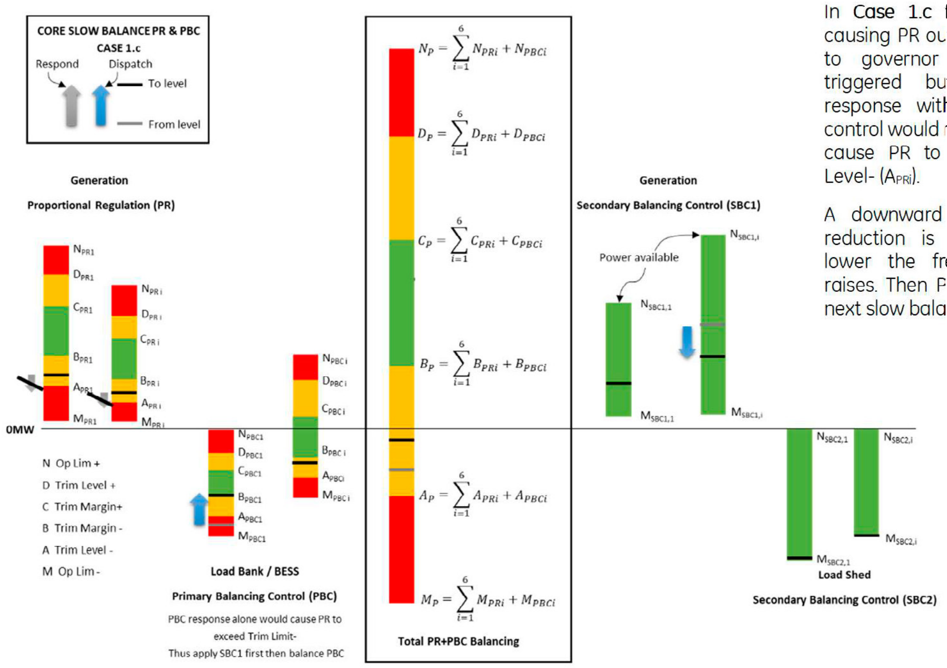
Figure 15 Case 1.b: High Frequency, PR resolved by SBC1 adjustment



In this case, when PR drops below 20 MW, PBC units are already close to their corresponding A thresholds (-2.5 and -9.5, respectively), and hence do not offer margin for trimming.

Slow Balancing, then, acts on SBC1 setpoints, lowering them so that the anchor generator is forced back within its green operating thresholds.

Figure 16 Slow Balancing Action, case 1.b



In **Case** 1.c frequency is high, causing PR output to be low due to governor control. PBC is triggered but delivering the response without a secondary control would raise frequency and cause PR to drop below Trim Level- (A_{PRi}).

A downward SBC1 generation reduction is deployed first to lower the frequency, and PR raises. Then PBC is raised in the next slow balancing cycle.

Figure 17 - Case 1.c High Frequency PBC trim resolved by balancing with SBC1 to avoid PR reaching trim limit

In case 1.c, PBC units reached the low red area, triggering a Slow Balancing action.

Since PR is in its low yellow, there is no trimming available between PR and PBC units, and a change of setpoint is dispatched to SBC1.

PBC units follow SBC1’s behaviour, but move in the opposite direction.

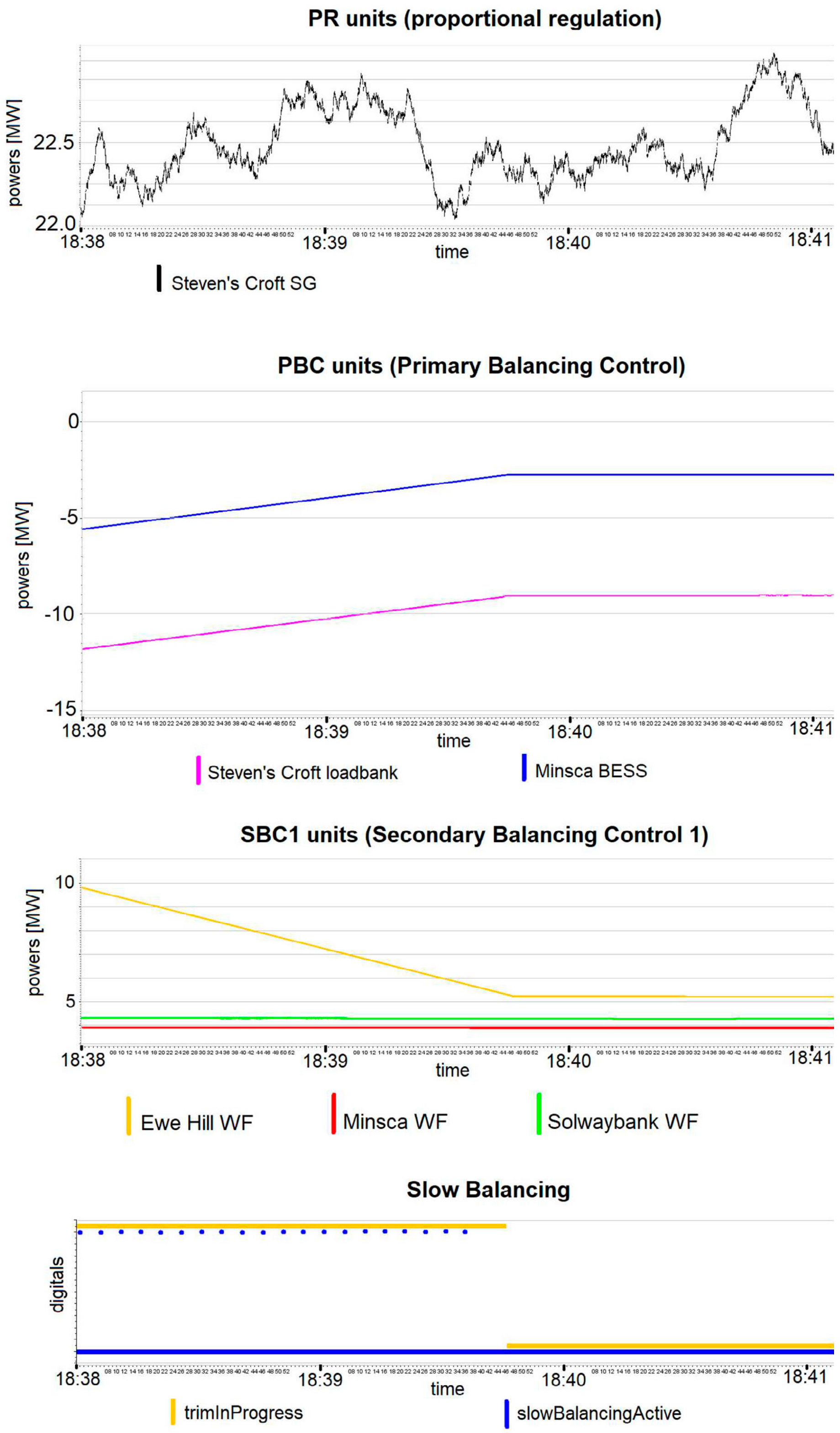


Figure 18 Slow Balancing action, case 1.c

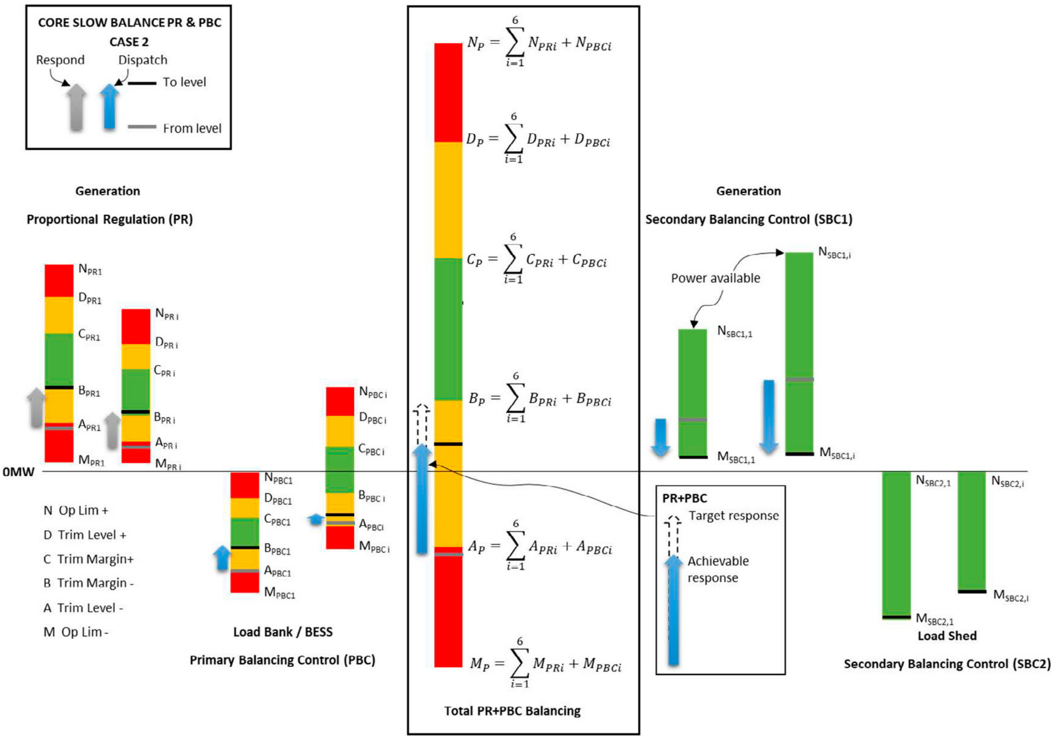


Figure 19 Case 2 High Frequency Total PR+PBC outside limits

In case 2, all PR and PBC units are in either low red or low yellow area. This triggers a Slow Balancing event, that lowers the setpoints of SBC1 units. PR operating points are driven up by the droop controller, while PBC setpoints are increased according to the SBC1 decrease that has already taken place. At the end of the Slow Balancing action, all PR and PBC units have reached their corresponding green operating area.

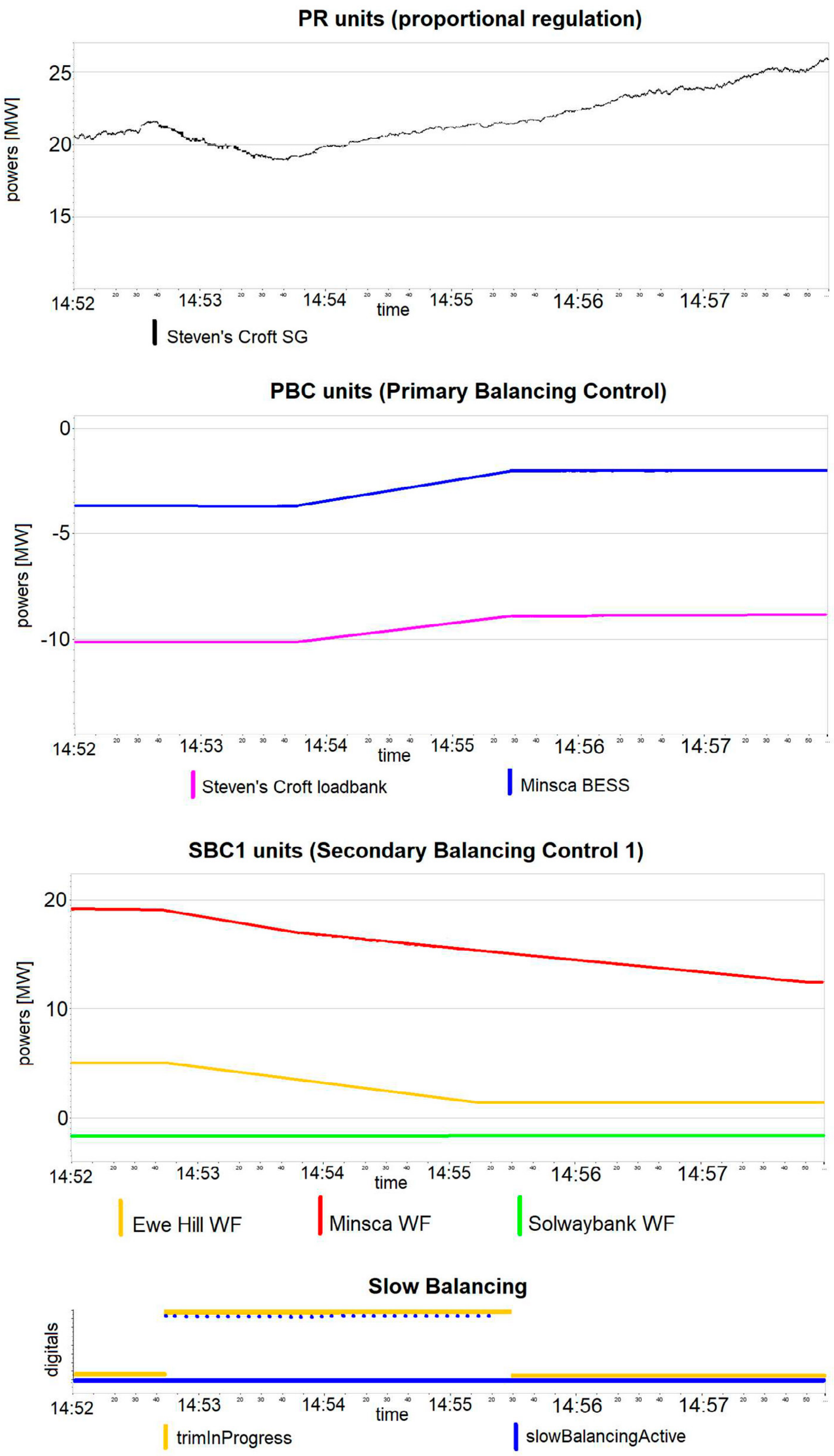


Figure 20 - Slow Balancing action, case 2

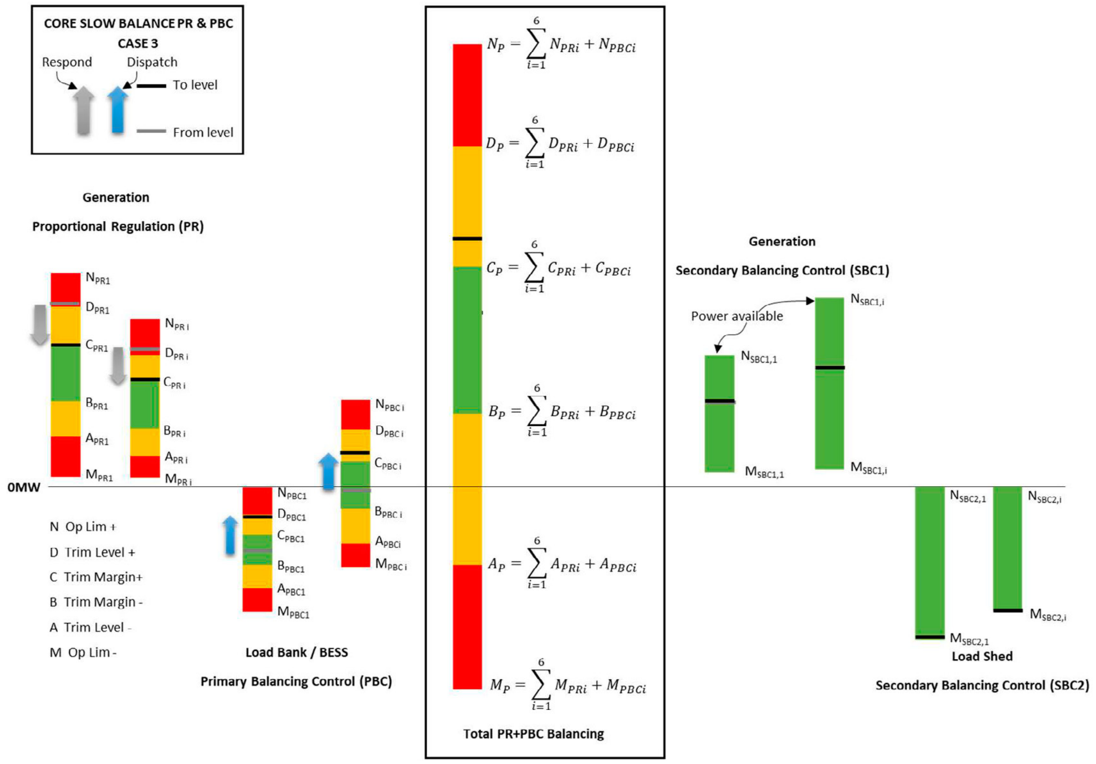


Figure 21 Case 3 Low Frequency, PR+PBC inside trim limits

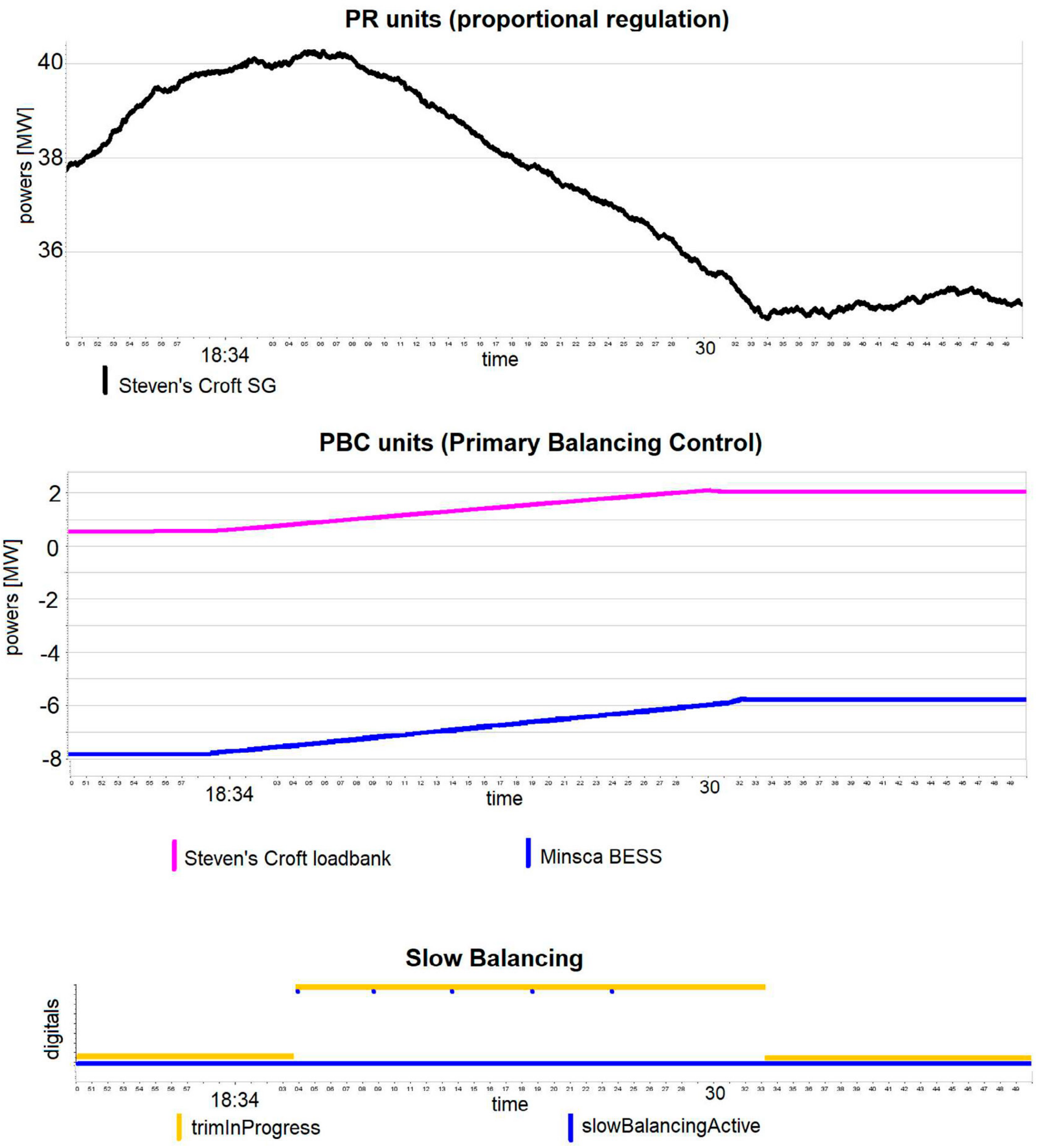


Figure 22 Slow Balancing action, case 3

In case 3, PR units enter the high red area, and are brought back into the green operating zone by a change in the PBC setpoints. When PBC units increase their powers, the droop action allows PR to decrease its power generation.

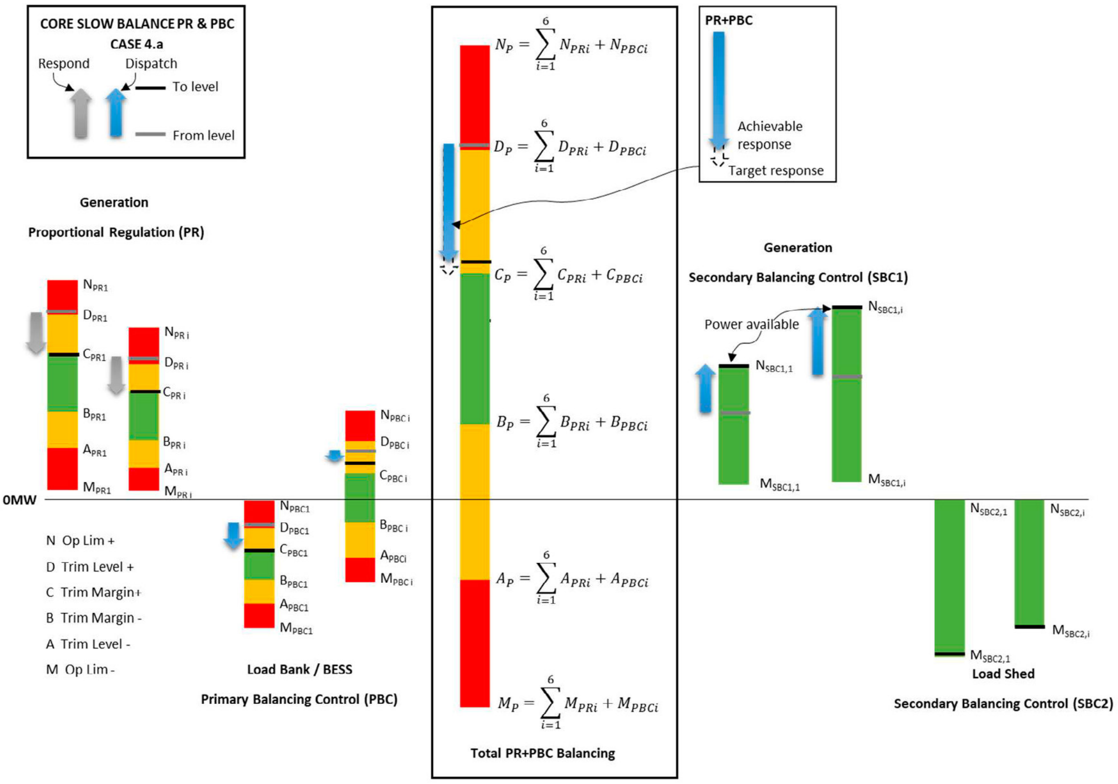


Figure 23 Case 4.a Low Frequency, PR+PBC outside trim limits due to load balance drift

When the anchor generator exceeds 40MW, PBC units are in their high yellow operating area. Then, the Slow Balancing acts on SBC1 setpoints, increasing the WF generation. PBC setpoints are gradually decreased following the behaviour of SBC1, but with opposite sign, while PR is driven down by its droop controller.

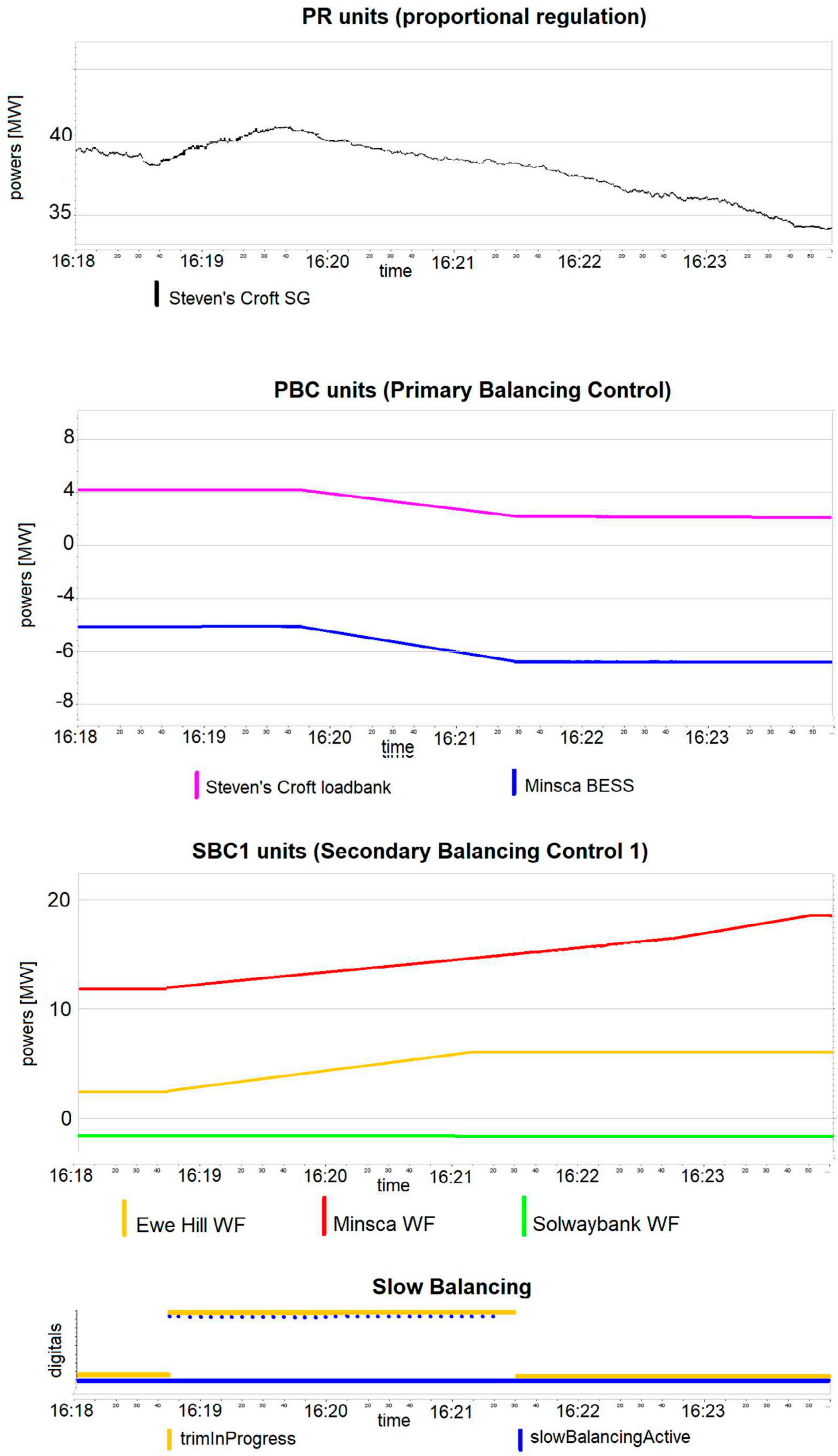


Figure 24 Slow Balancing action, case 4.a

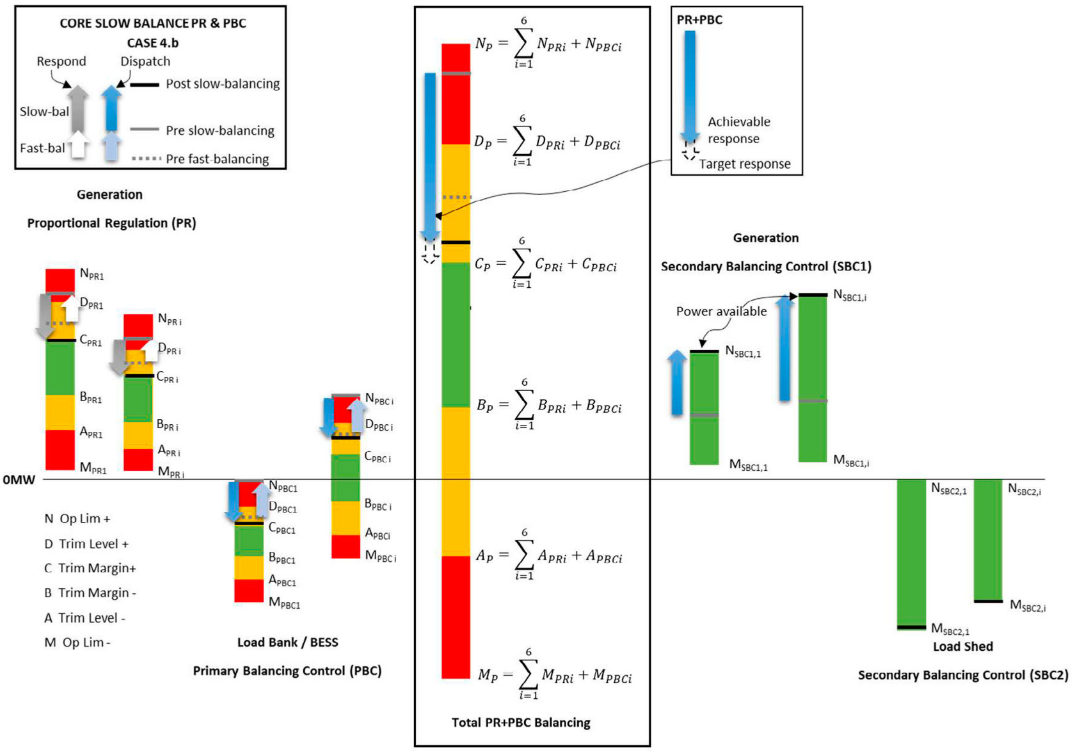


Figure 25 Case 4.b Low Frequency, PR+PBC outside trim limits due to Fast Balancing Event

Case 4.b is analogous to case 4.a, but PR+PBC units reach their high red operating areas following a Fast Balancing event. After the event is cleared (Fast Balancing being active prevents the Slow Balancing from being triggered), Slow Balancing acts to restore a condition with a greater margin for PR and PBC.

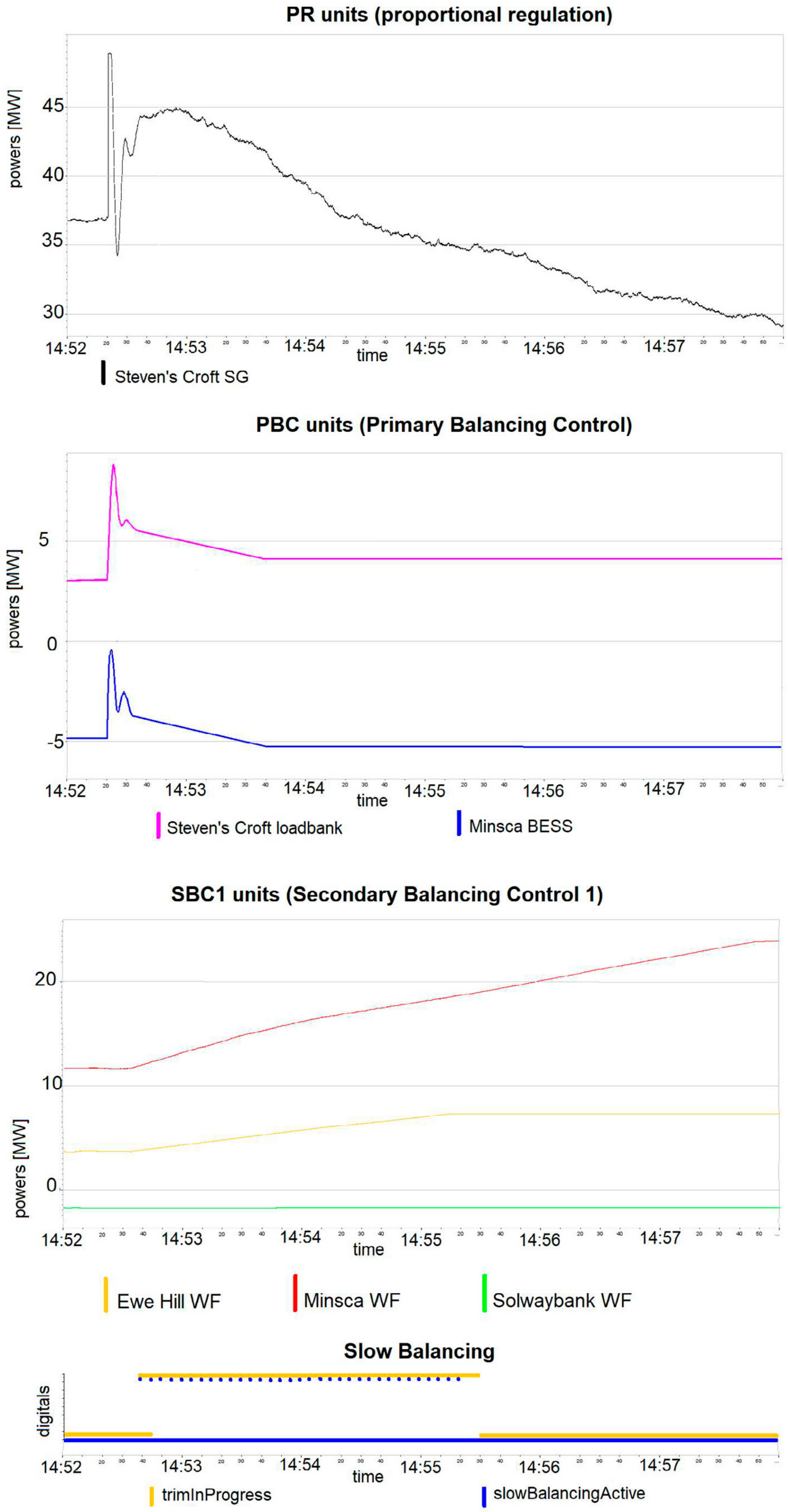


Figure 26 Slow Balancing action, case 4.b

Test 2.06	Multiple unplanned disturbance events including load and generator shedding	
Set-up	The purpose of the test is to show how the island responds to various disturbances including complex multiple event sequences. Start with the island running with all resources available with normal positive and negative control margins. All communications and control capabilities available. High load case applied.	
1. Procedure	Sequence of 2 load trip events separated by 10s. With the island running normally and resources available, initiate two load trip events, separated by a period of 10s. This is longer than the time required for fast balancing to act and stabilise and includes two cycle periods of slow balancing. Load loss events can be: Lockerbie Bus 2 (18MW) Langholm Bus 2 (14MW) DRZC should trigger a Fast Balancing response for both events. DRZC should initiate a Slow Balancing event after the first Fast Balancing is complete, and possibly another after the second event.	
2. Verification	Using PhasorPoint, confirm that the Fast and Slow Balancing responses are correctly implemented. Confirm that the DRZC system has correctly responded to maximise the use of PBC resource, and no negative interaction is created by the Slow Balancing actions. Review frequency and ROCOF behaviour, but note that double-contingency in 10s may be outside the performance requirement. The DRZC should improve behaviour but it may be outside the defined limits. Review ADMS observations and logs for consistency.	☑
3. Procedure	Sequence of 2 load trip events separated by 4s (repeat with 2s and 1s intervals) Restore to original condition of high load with all resources available. Repeat Test 1 above, but with 4s between events, thus events coming in less than one Slow Balancing cycle period. System should have time to reach a steady-state after the first event, but without Slow Balancing completing. Repeat with 2s and 1s wait between events, such that the system does not have time to stabilise at a new steady state before second event.	
4. Verification	Verify as per (2) above, also confirming change to SBC2 resource.	☑
3. Procedure	Sequence of 2 generation trip events separated by 10s	

	With the island running normally and resources available, initiate two generation trip events, separated by a period of 10s. This is longer than the time required for fast balancing to act and stabilise and includes two cycle periods of slow balancing. Apply 80% of high load levels totalling 36.7MW load, met by 25MW from generators to be tripped, plus 10MW from anchor generator and net 1.7MW from Minsca+BESS (BESS may be charging). Scenario may be adapted as required so that at least one of the trip event time separations in tests 3 or 5 causes an SBC2 load trip event. Generation loss events are windfarm trips with the towards the higher end of steady-state loading that would be allowed during island operation. Solwaybank windfarm (17MW) Ewe Hill windfarm (8MW) DRZC should trigger a Fast Balancing response for both events. DRZC should initiate a Slow Balancing event after the first Fast Balancing is complete, and possibly another after the second event.	
4. Verification	Verify as per (2) above., also confirming change to SBC2 resource.	☑
5. Procedure	Sequence of 2 generation trip events separated by 4s (repeat with 2s and 1s intervals) Restore to scenario in test (3) above. Repeat test (3) above, but with 4s between events, thus events coming in less than one Slow Balancing cycle period. System should have time to reach a steady-state after the first event, but without Slow Balancing completing. Repeat with 2s and 1s wait between events, such that the system does not have time to stabilise at a new steady state before second event.	
6. Verification	Verify as per (2) above.	☐
7. Procedure	Sequence of 1 generation trip event and generation emergency ramp-down Restore to scenario in test (3) above Generation loss events are Ewe Hill windfarm TRIP (8MW) Solwaybank windfarm Emergency Ramp (17→0MW at 1MW/s) The emergency ramp starts 1s after the Ewe Hill trip. DRZC should initiate a Fast Balancing response after the first trip. The volume of response may be increased by the subsequent ramp-down, but the ramp-down will not trigger another ROCOF event. Depending on the frequency behaviour, DRZC will either initiate a second Fast Balancing event based on Frequency Level threshold crossing, or a Slow Balancing event based on PR reaching its limit. A Fast Balancing event is likely to produce a further Slow Balancing event to restore the PBC and PR margins.	

8. Verification	Verify as per (2) above., also confirming changes to SBC 1&2 resources. Power balancing changes should all be acting to resolve the frequency and ROCOF issue, and the system should return within Trim Levels. However, the two consecutive events are outside the normal N-1 performance requirements for the island.	☑
9. Procedure	Loss of line connecting the anchor generator and load bank. **Revision:** This is not possible with the current setup.	
10. Verification	N/A	☐
11. Procedure	Loss of communications link to Steven's Croft followed by generation trip. In this case, the only PR resource (the anchor generator) becomes unobservable at the DRZC controller in Chapelcross. The DRZC should failover from triggering Slow Balancing using the power level of PR resource to triggering Slow Balancing from frequency level. The DRZC will operate as normal except for the frequency-based PR trigger and exclusion of the load bank from PBC. Starting from the normal high load condition, block communication from the Steven's Croft PMU and PhC (or set data to Invalid). DRZC will detect that there is no observable PR and will switch to frequency-based slow balancing trigger instead of PR power level based trigger. It will also detect lack of observability of Load Bank PBC and inactivate it in the Resource Table. Trip load (around 10MW) causing Fast Balancing response, followed by Slow Balancing response. Only Minsca BESS PBC and the windfarm SBC1 will respond. Restore to previous state, then ramp load down until Slow Balancing is triggered by Frequency Level backup to PR trigger. Anchor generator will apply PR response as normal in both cases, as this uses local measurements and control. No Fast Balancing will be applied, but Slow Balancing will occur using all resources except the Steven's Croft load bank (PBC). Restore communications from Steven's Croft PMU and PhC. **Note:** The case of loss of observability of all PR resource is not yet described in the DDS and should be added.	
12. Verification	Confirm using PhasorPoint that remaining resources are deployed normally. Confirm that Steven's Croft data has been detected as invalid and PBC is deactivated in the Resource Table. Confirm that DRZC does not attempt to control Steven's Croft Load Bank; the resource deployment uses only the remaining resources. Confirm that frequency is managed using the remaining resources and kept as close as possible within the limits up to the maximum resource capability.	☐

	Confirm that PBC returned to Resource Table when comms restored and DRZC switches back to using PR power level triggering.	
12. Procedure	Loss of communications link to Minsca windfarm and BESS followed by generation trip In this case, one each of the PBC and SBC1 resources are lost from the Resource Table, but the remaining resource still include PR, PBC and SBC1 capability. The DRZC processes should run as normal. Starting from the normal high load condition, block communication from the Minsca PMU (or set data to Invalid). DRZC will detect that the Minsca windfarm (SBC1) and BESS (PBC) have lost communication and will inactivate it in the Resource Table. Trip load (around 10MW) causing Fast Balancing response, followed by Slow Balancing response. Steven's Croft anchor PR, load bank PBC and any other SBC resources. Restore communications from Minsca PMU and PhC so that DRZC restores Minsca PBC and SBC1 into the Resource Table.	
13. Verification	Confirm using PhasorPoint that remaining resources are deployed normally. Confirm using PhasorPoint and/or PhasorController that Minsca data has been detected as invalid and the relevant PBC and SBC1 entries are deactivated in the Resource Table. Confirm that DRZC does not attempt to control Minsca PBC and SBC1; the resource deployment uses only the remaining resources. Confirm that frequency is managed using the remaining resources and kept as close as possible within the limits up to the maximum resource capability. Confirm that Minsca PBC and SBC1 is returned to the Resource Table when comms restored.	☐
Comments	2. Load tripping event must be at least 15-20s apart for the Fast Balancing event to be cleared between events. Fast Balancing will dispatch more resource during a multiple event case if the RoCoF becomes steeper or if frequency deviation term becomes greater than the RoCoF-based term. Frequency tends to be more poorly controlled when events are more closely spaced as frequency does not recover between trips. However, if two events are very closely spaced, the frequency will act as if it was only a single event and Fast Balancing will act on the overall effect on frequency and RoCoF. 4.-6. Sudden generation loss triggers a Fast Balancing event. In case of a high-load scenario, the loss of two generation units causes load shedding. In this case as well, a Fast Balancing event is cleared in 10-15 s, thus not allowing the frequency to recover if trips are 4s apart. 8. The first generation trip triggers the Fast Balancing, while SBC1 units ramping down do not. 0MW generation availability is received by the DRZC from both units, and hence the Slow Balancing might shed loads (if high loads are currently connected to the network). 10. The current simulation setup does not allow the system to run after the anchor generator is disconnected from the rest of the zone. Even if it could be simulated, the DRZC does not at this stage accommodate islanding within the zone. Further work would be needed to detect	

	islanding within the zone, use the load bank to balance the anchor, and shutdown the second island. Only the part of the island including the anchor could be maintained safely due to earthing, protection, and the presence of a droop-controlled unit for frequency regulation.

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Figure 27 depicts the system's behaviour following a double load trip. The two loads trip 10s apart: the first event happens at 10:20:21, triggering a Fast Balancing action; the second event happens at 10:20:31, when the system has not recovered fully from the previous load trip. Fast Balancing stays active for 15s, then it times out for 5s, allowing the Slow Balancing to deliver one change of setpoints. In particular, the change of setpoints involve tripping a windfarm; in this case, tripping a windfarm is needed to allow PBC units to recover. When less extreme cases are considered, a change of setpoint of windfarms would be followed by a ramp, rather than a sudden trip. After the Slow Balancing action, since the frequency event is still on at the end of the 5s pause, Fast Balancing resumes, clearing the event at 10:20:49.

The Slow Balancing in between the two Fast Balancing actions allows PBC units to recover: when Fast Balancing times out, both PBC units are working at their minimum operating point, and there is no margin left for lowering the frequency further. After the frequency event is cleared, Slow Balancing is activated again to bring PR and PBC units back to their green operating areas.

Fast balancing has a component due to RoCoF that triggers on the sudden power balance changes, and another component due to frequency difference from nominal. If a second event occurs while fast balancing is active, and if it shows a lower ROCOF than the first, it is likely that the frequency deviation term would be the trigger for a second fast balancing event.

Overall, the island's frequency and RoCoF were kept within acceptable thresholds for the whole duration of the quoted example. Some more tuning can be made in the future to aim to speed up the response of the Fast Balancing, in order to clear events more quickly, but the system seems to be relatively resilient against load trips.

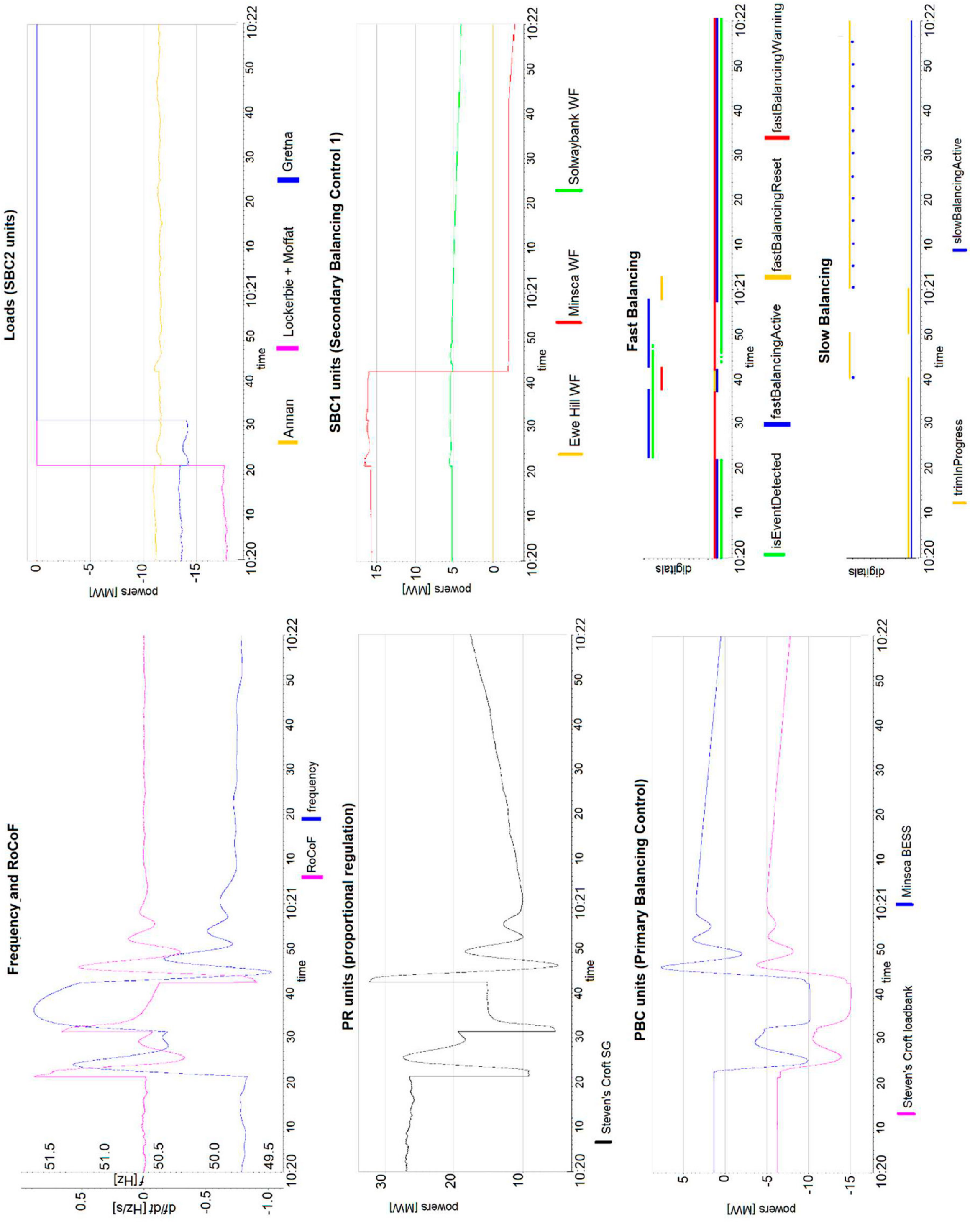


Figure 27 System's behaviour following a double load trip, 10s apart

Test 2.07	Demonstrate frequency level event responses and compare ROCOF triggering	
Set-up	The purpose of this test is to demonstrate triggering PBC by a frequency level event and compare this with a ROCOF-based trigger event of similar size. Level event triggering is intended for events that progress more slowly than the sudden load pickup or trip events that cause ROCOF-based triggering. This may occur because of a generator ramping down, a change of windspeed, or several smaller events. Start with the island running with all resources available with normal positive and negative control margins. All communications and control capabilities available. High load case applied. The test involves comparing the loss of a windfarm as a ramp-down leading to a frequency level event compared with a trip. Solwaybank can be used as the test, running at output of around 20MW.	
1. Procedure	Determine response to windfarm trip and ROCOF-based PBC triggering. Trip windfarm, leading to large ROCOF and Fast Balancing triggering. This may be followed by Slow Balancing.	
2. Verification	Confirm using PhasorPoint that the balancing process applies PBC and SBC as expected. Review frequency behaviour, noting the frequency deviation and ROCOF values reached.	☑
3. Procedure	Ramp down windfarm to 0MW at 1MW/s. The aim is to initiate frequency level-based Fast Balancing triggering by reaching the frequency level trigger without ROCOF triggering and without initiating Slow Balancing due to PR Trim Level. Note that this may not be achieved at this ramp rate and the following tests explore different ramp rates.	
4. Verification	Using PhasorPoint, review the frequency behaviour for filtered and unfiltered frequency, and ROCOF behaviour, and check which of the following should apply Fast Balancing ROCOF-based trigger of PBC Fast Balancing Frequency-level-based trigger of PBC Slow Balancing PR output level action Confirm that the DRZC action is consistent with the expectation given the frequency behaviour. Confirm that frequency is adequately managed in the event.	☑
5. Procedure	Repeat test (3) with different ramp rates.	
6. Verification	Repeat verification (4) for different ramp rates	☑

Comments	Fast Balancing events are correctly triggered by RoCoF exceeding ±0.25 Hz/s for 0.06s, or frequency exceeding 50.0 ±0.3 Hz for 0.2s.

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

4.4 Energising Transformers and Resynchronisation

Test 3.00	Energise 132/33kV transformers from 33kV side	
Set-up	This test demonstrates the impact of 132/33kV transformer energisation on the system, particularly on voltage profile. The differences between high load and low load case will be compared. While DRZC is designed for frequency and power balance rather than voltage control, the test will demonstrate observability by PMUs, and may indicate ways in which the DRZC may be enhanced in future to manage voltage profile. The network is initially set up with the high load scenario, with all balancing resources available. Breakers are open at both sides of both 132/33kV transformers.	
1. Procedure	Close 132/33kV Grid Transformer T1 33kV breaker. Wait for voltage to return to steady-state value. Close 132/33kV Grid Transformer T2 33kV breaker.	
2. Verification	Using PhasorPoint, review the voltage response following both transformer energisation events. Confirm that DRZC does not trigger any Fast or Slow Balancing actions in response to the energisation.	☑
3. Procedure	Revise the loading condition to lightly loaded scenario, reducing generation as required to balance. Close 132/33kV Grid Transformer T1 33kV breaker. Wait for voltage to return to steady-state value. Close 132/33kV Grid Transformer T2 33kV breaker.	
4. Verification	Using PhasorPoint, review the voltage response following both transformer energisation events. Confirm that DRZC does not trigger any Fast or Slow Balancing actions in response to the energisation. Compare the results with test (1) above, showing the difference between energisation in lightly loaded and heavily loaded conditions.	☑
Comments	Both sides of T1 and T2 can be energised without triggering a fast or Slow Balancing response. Frequency remained stable, and transients in Chapelcross busbar voltages did not exceed 0.001 p.u.. Transients at Steven’s Croft were, in general, smaller. No significant difference can be noted between high and low load scenarios.	

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

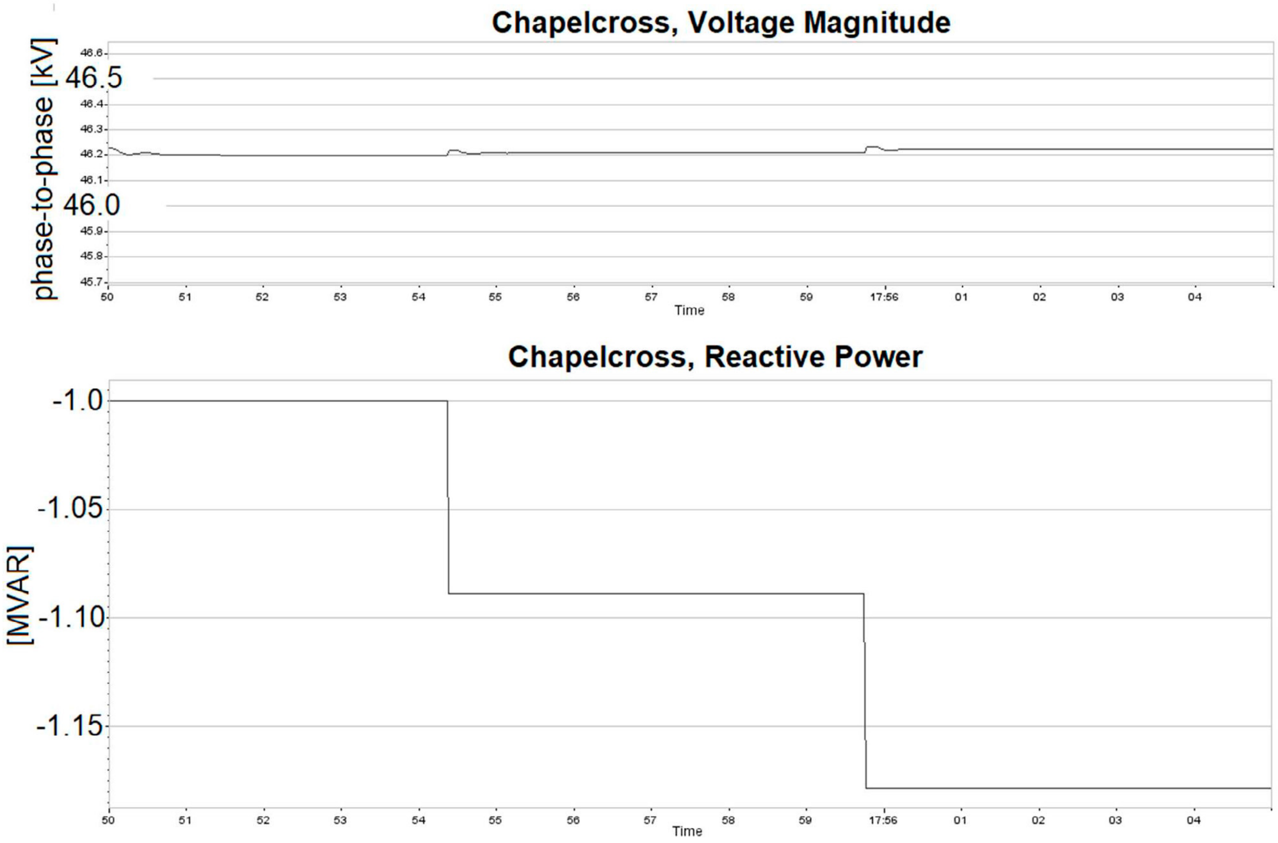


Figure 28 - Energisation of the 33kV sides of T1 and T2. Voltage and reactive power behaviour at Chapelcross.

Test 3.01	Demonstrate resynchronising control and view in PhasorPoint	
Set-up	With the power system in the high load condition and the 132/33kV transformers energised, the resynchronisation process is demonstrated across the 132kV breakers. The external network is represented by an impedance and a synchronous generator whose capacity is much larger than the anchor generator's. The external grid frequency is adjusted to an off-nominal average value (e.g. 50.1Hz) and subjected to random slow perturbations to show the ability of the DRZC to adapt to different grid frequencies. The resynchronisation readiness is observed in PhasorPoint and the breaker closure controlled by the DRZC synchrocheck function. A synchrocheck function is also applied by the DRZC to control breaker closure. In the real situation, frequency and angle differences are constantly changing between the island and the transmission grid. It is necessary to replicate this movement as the islanding identification and synchrocheck functionality depend on the system moving in and out of alignment. Loads within the island are stimulated to create random small-disturbance deviations. Random noise is created, and filtered with a lowpass filter (cut-off 2Hz) and added to the loads in the island. This results in random deviations of frequency and angle. Additional steady-state changes in windfarm output and loading would also help to represent the variations in the real system.	
1. Procedure	This test demonstrates observability of the island condition in PhasorPoint and the islanding detection in PhasorController. PhasorPoint receives synchrophasor data from within the island and at the 132kV transmission system side. The Islanding application shows the frequency and angle difference between the two sides of the split and presents an islanding indicator. In PhasorPoint's Islanding application view, select two phasors from the transmission side and the distribution side at Chapelcross cross and select the view of angle, frequency and voltage differences. There is also an islanding detection function in DRZC; the status values of islanding detection are sent to PhasorPoint and ADMS. This indicator can be viewed in PhasorPoint's live and historic data viewer. Run in island mode, show islanding indicator from DRZC and in PhasorPoint islanding app	
2. Verification	Using PhasorPoint's islanding application, view the phasor rotation and frequency difference between monitoring locations. Using the PhasorPoint islanding detector, confirm that islanding is detected in the monitoring system (yellow or red indicator). Using PhasorPoint's data viewer, confirm that the DRZC's islanding status indicator is raised. Confirm that the DRZC islanding status is received and observable in ADMS.	☑

3. Procedure	Operator initiates Resynchronising Control to assist with aligning frequency between islands. From ADMS, select the option to initiate DRZC's Resynchronising Control. DRZC measures the frequency difference between the island and the transmission grid, using the lowpass filtered frequency. If frequency difference is outside a threshold, a power adjustment is made in the zone and with PR control, the island will settle at a new frequency. This may repeat if frequency difference between the island and the transmission network diverges over time. Once frequency and angle are within a set threshold, the Resync Ready flag raised and sent to ADMS. Frequency will vary with load variations and the Resync Ready flag may lower and raise again.	
4. Verification	Confirm that Islanding is indicated in the DRZC flag, PhasorPoint and ADMS. Review and compare the direct PMU frequency and the filtered PMU frequency, checking that filtered frequency is following the unfiltered version, but without fast random noise. Observe the filtered and unfiltered frequency difference signals in PhasorPoint. Confirm at least one action of Resynchronisation control to draw the frequency of the island towards the infinite bus frequency. Confirm that frequency is aligned sufficiently and the Resync Ready flag is raised.	☑
5. Procedure	Operator arms synchrocheck function. Checksync arming of the Chapelcross T1 132kV breaker is initiated by an operator through the ADMS, which is sent to the DRZC. The DRZC checks the unfiltered frequency and angle differences against pre-defined settings. Once the angle and frequency differences are both within the thresholds, the DRZC will issue a breaker closure command to the transformer T1 132kV breaker at Chapelcross. The breaker closure signal is sent as an IEC104 message to the PhC_FIU, and then converted to GOOSE to apply to the OPAL-RT system. The 132kV breaker is closed at Chapelcross transformer T1, resynchronising the island to the main grid. Transformer T2 132kV breaker is closed manually from the ADMS once it is clear that the resynchronisation has been successful. There is no need for applying the synchrocheck relay function on the second breaker in the test as the angles and frequency will be aligned.	
6. Verification	Confirm using PhasorPoint's islanding view that the zone is initially islanded and that the resynchronisation is successful. The point of resynchronisation can be observed in PhasorPoint as voltage phase angle indicators, which rotate relative to each other during island operation, becoming locked into alignment as the breaker is closed, usually with a small transient.	☑

	Confirm that the breaker remains closed and the angles and frequency stay in alignment. Confirm that the islanding indicators are cleared in DRZC, PhasorPoint and ADMS.	
Comments	The resynchronising function is able to align the island frequency to the external frequency. When the procedure is completed, resyncReady signal is raised to the ADMS. Breakers closure can be enabled by the ADMS, and, after they close, the islanding signal switches from TRUE to FALSE. Control to adjust the frequency difference reduces the transient disturbance, as well as reducing ROCOF in the zone. This reduces the risk of protection trips from the closing event e.g. due to ROCOF, vector shift, power swing, voltage level etc., as well as improving the likelihood of successful closure.	

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

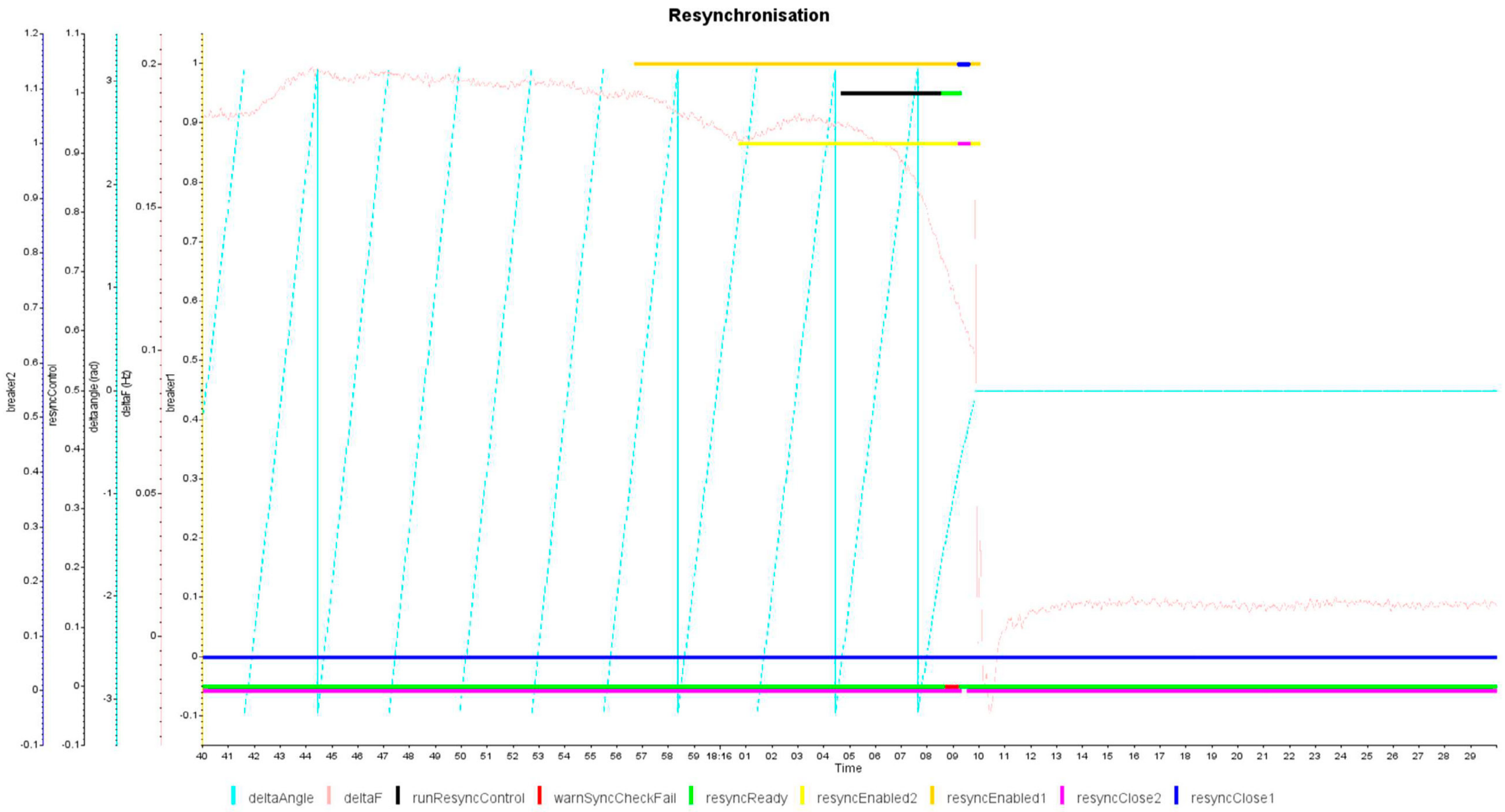


Figure 29 Resynchronisation action, frequency difference, angle difference, DRZC digitals

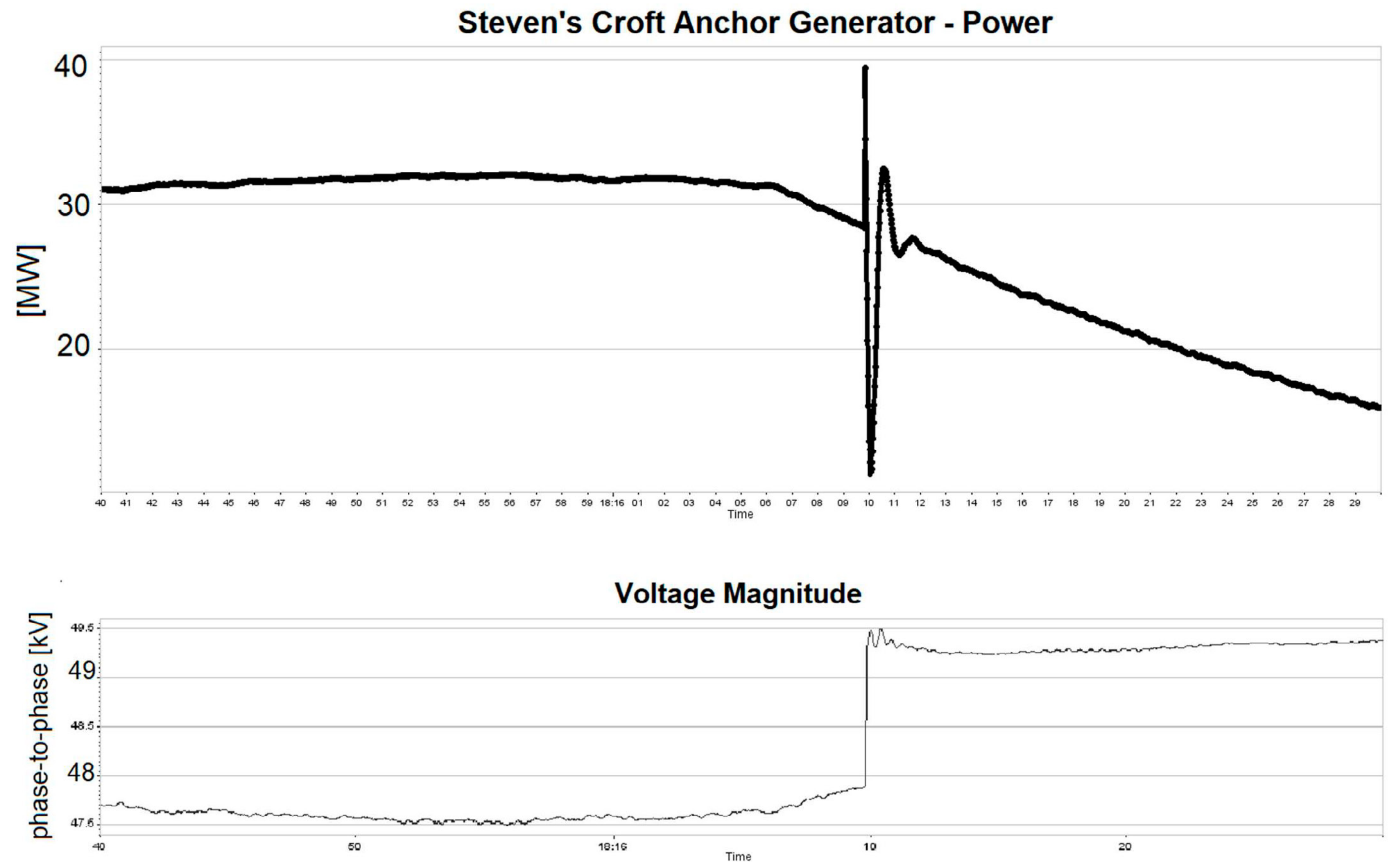


Figure 30 Resynchronisation action – Power behaviour at Steven's Croft and Voltage behaviour at Chapelcross

4.5 Termination of Island Operation

Test 4.00	**Restore network to grid-connected mode using GTC**	
Set-up	The network is in the state immediately following the resynchronisation (above). The zone is connected to the external system.	
1. Procedure	Group telecontrol is initiated to switch the network to the grid-connected state. This includes earthing transformer switching. The termination process is carried out as a GTC in ADMS without interaction with the DRZC. OPAL-RT via FIU is used as the network emulator to receive and confirm the commands. Note that termination in the real system may include switching the anchor generator back to constant power control mode, but there may be an advantage is continuing frequency responsive PR operation. Further work is needed to determine whether PR should be active, inactive or active with revised droop setting. The mode selection is assumed here to be a manual process co-ordinated between operators in the control room and at the anchor generator plant, and out of scope for the automated system.	
2. Verification	Confirm using OPAL-RT and ADMS that the earthing point is applied at the 33kV side of the Chapelcross transformers and removed at Steven's Croft anchor generator in the correct order, without the system being unearthed at any point. Record the length of time from start to completion of the termination sequence.	
Comments	Due to limitations in the OPAL-RT modelling, it is not possible to switch the anchor generator from droop to constant power mode.	

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

Test 4.01	Display ongoing resource margins	
Set-up	With the zone connected to the external transmission system, confirm that the resource margins of the controllable plants remain observable to the control room operators. The network is in the state after the termination process. The ADMS has a display of the total active power available resources in each category (PR, PBC, SBC1&2).	
1. Procedure	With all resources active, DRZC will calculate the sum of the positive and negative operating limits, and the total power in each category. The summary information will be sent from DRZC to ADMS where it will be observed in a summary table. The individual plant conditions are also shown in terms of upper and lower power available and the present operating point. Power available is varied, as is expected by changes in wind power. This results in variation of the operating limits in SBC1. Loads are varied to demonstrate changes in SBC2. Frequency is varied at the infinite bus to demonstrate changes in PR. Load bank and battery outputs are varied to demonstrate changes in PBC present operating conditions.	
2. Verification	Confirm that the changes in operating limits and present operating power are reflected in the summary table and individual plant conditions observed in ADMS.	☑
Comments	Resources margins are correctly displayed in the ADMS.	

Outcome ☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

4.6 Full Process Walk-through with and without disturbances

This set of tests demonstrates the end-to-end process of starting up the island, energising loads and running the island with the balancing processes running. The island is then resynchronised and the process terminated. The full sequence is demonstrated for different loading and generation scenarios, and depending on the test case there can be unplanned disturbances added to the case.

This set of tests is intended to provide a full demonstration of the functioning of the restoration zone control system and its interaction with the ADMS automation and operator intervention. In particular, the series of tests is intended to show how the DRZC system relieves the operator of the responsibility of managing frequency control and balancing in the island, so that the control room has high level observability of the process without the burden of real-time balancing. The demonstration also shows the resilience that the DRZC system provides through fast co-ordination of resources to ride through unplanned events.

Test 5.00	**High-load, high power available scenario; energisation and load pickup to resynchronisation and termination without unplanned events.**	
Set-up	The Chapelcross network is configured in OPAL-RT HiL simulation with the high load scenario described in Section 3, with full power available from renewable resources, but with load and generation de-energised. The network is set to a post-blackout scenario with most generator breakers open, some loads disconnected from underfrequency load shedding. Earthing transformers are connected as for grid-connected operation. The network is observed by the ADMS and PhasorPoint, and the PhasorController DRZC is available. The external network is represented by an infinite bus behind an impedance. The state of the external network should not affect the island operation, and so it can be energised throughout. The frequency of the external network should be off-nominal (e.g. about 50.2Hz) to demonstrate resynchronisation. Cold load pickup is assumed to be 1.5x the maximum steady state load. It is expected that the cold load pickup should reduce to steady-state load in 30 minutes in reality, but to compress the test time periods, cold load level ramps down to steady-state load in 2 minutes in the test setup. Filtered random load variation up to +/-5% of operating load is applied throughout the simulation to create realistic frequency perturbations.	
1. Procedure	Stage 1 Network Initialisation The "network black" state is confirmed by the ADMS and DRZC. The operator issues a GTC command in ADMS to initialise the network, which carries out the following actions: 1. Reconfigures the earthing transformer switches	

	2. Sets the load and generator breaker positions to the expected state to start the procedure 3. Logs actions and confirms success of the operation. In this case, all actions are successful and the network is ready to start.	
2. Verification	PhasorPoint and ADMS show zero volts throughout the network from the PMU and SCADA monitoring respectively. The “network black” state is confirmed. The Network Initialisation GTC reports completion without errors. Manual inspection of the breaker states in the ADMS network view confirms that the network has been switched to the required startup state.	☑
3. Procedure	Stage 2 Anchor startup The scenario is updated by running up the anchor generator, with power balance achieved using the load bank. It is assumed that this would be done manually in the real situation by the anchor generator operator who would have control of load bank as well as the generator. Once both the anchor generator and the load bank are within normal operating limits, the ADMS and PhasorPoint should confirm that the anchor is in the correct state to start energising the network. In reality, the anchor operator would confirm by a voice call to the control room that the anchor is ready, but the control room operators confirm from the measurements that the anchor and load bank are stable and at suitable operating points.	
4. Verification	Confirm using PhasorPoint that the anchor and load bank are stable and in a suitable operating point to continue with the process. Confirm that ADMS receives and displays an indicator consistent with the anchor being ready. Thus, when the control room operator receives a voice call from the anchor operator, the measurements confirm that the process can move ahead.	☑
5. Procedure	Stage 3/4 Energisation, load pickup and island running The network energisation process is continued through the automated sequences in the ADMS. The network is energised from the anchor generator to Chapelcross, and the primaries are picked up in a pre-defined sequence. Circuits with devices that are included in balancing control are picked up early in the sequence and activated in the DRZC Resource Table. The interaction between the ADMS and DRZC is demonstrated with some load pickup stages requiring priming while others do not. In this case, all loads may be picked up and no unplanned disturbances are introduced.	
6. Verification	Confirm that the ADMS automation process stages to pick up circuits and load operate as expected. Confirm that resources are activated in the DRZC Resource Table and the expanded capability shows in the ADMS summary and detailed status views.	☑

	Confirm that the DRZC and ADMS select priming when required and that the priming process is applied correctly. Confirm that primary and secondary balancing are applied correctly and that the frequency and ROCOF are maintained within limits.	
7. Procedure	Stage 5/6 Resynchronisation and Termination The operator initiates Resynchronisation Control through the ADMS and the DRZC applies balancing control to bring the frequency of the island into near-alignment with the external network. The DRZC determines when frequency and angles align across the resynchronisation boundary and raises a flag to indicate that the network is ready to resynchronise. Apply a load change to exercise the Resynchronisation Control, showing frequency brought back to alignment. The operator initiates the Synchrocheck function. The DRZC waits for angle and frequency difference to move into alignment and then closes the breaker to resynchronise to the grid. The DRZC detects the grid-connected behaviour and lowers the Islanded status, and the flag status change is observed in the ADMS. The operator initiates the Termination process in the ADMS, which restores the earthing points and sends a command to protection devices to deploy the normal grid-connected protection settings group.	
8. Verification	Confirm using PhasorPoint Islanding application view that the system is in islanded operation. Select angle and frequency difference view across the resynchronisation boundary (132kV breaker at Chapelcross T1 transformer). Confirm that DRZC deploys control to bring island frequency into alignment with the external network. Confirm that when the island frequency again deviates from the network due to load changes, the DRZC will apply another alignment process. Confirm using PhasorPoint that the Synchrocheck function operates as expected, closing the breaker when frequency and angles are in alignment. Review the transient power swing following the breaker closure, showing that the transient is relatively small and not likely to cause breaker re-opening. Confirm using ADMS network view that the Termination sequence completes successfully, and the earthing breakers are reinstated for grid-connected operation.	☑
Comments	A scenario with high loads, high generation availability, and no unplanned events was run from initialisation to termination. Priming was called by the automated re-energisation process for 3 out of 4 loads. Frequency and RoCoF were kept within acceptable limits.	

Outcome ☑ GE Reporting ☑ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Test 5.01	**Medium load, low power available scenario; energisation and load pickup to resynchronisation and termination without unplanned events.**	
Set-up	The Chapelcross network is configured in OPAL-RT HiL simulation as in Test 5.00, with the difference that the median load level scenario is used and there are low generation resources. In the low generation scenario, the renewable generation has ≤20% of full power available. In this scenario, it is intended that some loads cannot be picked up.	
1. Procedure	Stage 1 Network Initialisation Same as Test 5.00 above.	
2. Verification	Same as Test 5.00 above.	☑
3. Procedure	Stage 2 Anchor startup Same as Test 5.00 above.	
4. Verification	Same as Test 5.00 above.	☑
5. Procedure	Stage 3/4 Energisation, load pickup and island running Similar to Test 5.00, the process of energisation proceeds using the automation in ADMS. However, there will be cases where there is insufficient resource to pick up some loads, even with priming. The ADMS automation will report “completed with errors” and the operator may apply a manual switching process to pick up load in smaller blocks. No unplanned disturbances are introduced. The operator uses the standard ADMS network view to apply load pickup in smaller steps with observability of the pickup capability from DRZC and the expected pickup value from ADMS.	
6. Verification	In addition to confirmation process in Test 5.00: Confirm that ADMS identifies cases in which some load pickup cannot be achieved without risk of excessive frequency/ROCOF deviation, even with priming. Confirm that these load pickup cases are not applied automatically but are referred to the operator. Confirm that the operator can compare the pickup capability and the expected load pickup value for a more granular manual process. Confirm that primary and secondary balancing are applied correctly within the constraints of available resources, and that the frequency and ROCOF are maintained within limits.	☑
7. Procedure	Stage 5/6 Resynchronisation and Termination Same as Test 5.00 above.	
8. Verification	Same as Test 5.00 above.	☑

Comments	A scenario with medium loads, low generation availability, and no unplanned events could run from initialisation to termination as expected. Priming was never called by the automated load re-energisation process. Frequency and RoCoF were kept within acceptable limits.

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

Test 5.02	High-load, high power available scenario with unplanned load and generator tripping including multiple event sequences.	
Set-up	The Chapelcross network is configured in OPAL-RT HiL simulation as in Test 5.00.	
1. Procedure	Stage 1 Network Initialisation Same as Test 5.00 above.	
2. Verification	Same as Test 5.00 above.	☑
3. Procedure	Stage 2 Anchor startup Same as Test 5.00 above.	
4. Verification	Same as Test 5.00 above.	☑
5. Procedure	Stage 3/4 Energisation, load pickup and island running Similar to Test 5.00, the process of energisation proceeds using the automation in ADMS. Generation and storage sources are picked up along with load.	
6. Verification	Same as Test 5.00 above.	☑
7. Procedure	*Single generation loss: frequency/ROCOF expected to stay within limits (baseline).* One generation trip is introduced leading to a loss of MW that is within the capability of the island to stay within the frequency and ROCOF performance limits. DRZC will activate fast and slow balancing to maintain the stability of the island.	
8. Verification	Confirm using PhasorPoint that single generation loss is stable and within defined frequency / ROCOF performance limits of the zone.	☑
9. Procedure	*Sequential double generation loss: frequency/ROCOF expected to stay within limits.* Restore the operating point to the pre-event condition (end of Step 5). Trip two renewable generation sources e.g. Minsca and Ewe Hill windfarms, for which the combined total is smaller than the available controllable resources. As above, DRZC will activate fast and slow balancing to maintain the stability of the island. Although this is an N-2 scenario, if the total generation loss is within the secured capability of the island, the frequency should remain stable. Repeat test with different sizes of gaps between events (0s, 1s, 2s, 5s, 10s) to compare the response of the DRZC.	
10. Verification	Review frequency performance in PhasorPoint. Confirm that the DRZC action is sufficient for keeping within frequency performance limits.	☑
11. Procedure	*Double generation loss: frequency/ROCOF expected to exceed limits.* Restore the operating point to the pre-event condition (end of Step 5).	

	Trip two larger renewable generation sources e.g. Minsca and Solwaybank windfarms, for which the combined total is greater that the available controllable resources. As above, DRZC will activate fast and slow balancing to maintain the stability of the island, but has insufficient resource to halt the frequency decline. Repeat test with different sizes of gaps between events (0s, 1s, 2s, 5s, 10s) to confirm that the DRZC system is able to respond to multiple event sequences.	
12. Verification	Review frequency performance in PhasorPoint. Confirm that the DRZC action is helpful but not sufficient for keeping within frequency performance limits.	☑
13. Procedure	Stage 5/6 Resynchronisation and Termination Same as Test 5.00 above.	
14. Verification	Same as Test 5.00 above.	☑
Comments	A scenario with high loads, high generation availability, and unplanned generation loss was run from initialisation to termination. 8. Single generation trips were handled well by the system, Fast Balancing kept frequency and RoCoF within acceptable boundaries, while Slow Balancing re-distributed the generation among the units that were still active, and managed to bring PR and PBC units within trim margins. 10. A double generation loss, if small enough (e.g. Minsca + Ewe Hill, about 12 MW loss overall), can be handled by the DRZC without big frequency deviations. 12. A large double generation loss can lead to a significant frequency drop. The narrower the time interval between the trips, the worse the results. Simultaneous loss of Minsca+Solwaybank (about 17 MW overall) caused a frequency drop to 47.9Hz, Fast Balancing action was triggered, followed by a load shedding. The frequency stabilised after about 50s. When the losses were 10s apart, instead, the frequency did not drop below 48.9Hz. In general, the effect of large unplanned events depends on the power level of PBC units just before they happen. E.g. a generation loss will cause worse effects if PBC units are operating in the high yellow band, rather than in the green or low yellow. This condition is mitigated by the Slow Balancing, which prevents PBC units from working steadily in the red bands Since the response of the system to large events is dependent on the PBC margin before the event, it may be beneficial to broaden the red bands, thus narrowing the operational range for normal operation and keeping the controllable resource closer to its mid-point and maintaining larger margins for control. Fast and Slow Balancing were able to recover the system after the events, and resynchronisation and termination were successfully achieved.	

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☑ Customer witnessed ☐ Approved	Signature Date	Signature Date

☐ Not Complete ☐ Failed		

Test 5.03	High-load, high power available scenario with unplanned network tripping.	
Set-up	The Chapelcross network is configured in OPAL-RT HiL simulation as in Test 5.00.	
1. Procedure	Stage 1 Network Initialisation Same as Test 5.00 above.	
2. Verification	Same as Test 5.00 above.	☑
3. Procedure	Stage 2 Anchor startup Same as Test 5.00 above.	
4. Verification	Same as Test 5.00 above.	☑
5. Procedure	Stage 3/4 Energisation, load pickup and island running Similar to Test 5.00, the process of energisation proceeds using the automation in ADMS. Generation and storage sources are picked up along with load.	
6. Verification	Same as Test 5.00 above.	☑
7. Procedure	*Trip line to primary transformer, shedding load.* Loss of a feeder between Chapelcross and a primary transformer results in net loss of load. DRZC may initiate a fast balancing event to reduce PBC (i.e. reduce BESS output or increase load at load bank), which may be followed by a slow balancing event.	
8. Verification	Confirm using PhasorPoint that frequency and ROCOF are contained within performance limits	☑
9. Procedure	*Trip line to Minsca WF and BESS disconnection.* This results in loss of generation, load and PBC capacity. The DRZC system will remove the relevant PBC and SBC1 resources from the Resource table. If the net power balance changes sufficiently to initiate a fast balancing response, this will be provided by the remaining resources.	
10. Verification	Confirm using PhasorPoint that frequency and ROCOF are contained within performance limits.	☑
11. Procedure	*Trip line leading between anchor/load bank and Chapelcross.* Not possible within the simulation capability.	
12. Verification	N/A	☐
Comments	A scenario with high loads, high generation availability, and unplanned network tripping was run.	

	8. Load trips triggered Fast Balancing events, followed by Slow Balancing. The DRZC was able to keep the system within acceptable operating conditions, stabilising the frequency and re-distributing the power generation among units. 10. The loss of Minsca WF+BESS triggered a Fast Balancing event, followed by Slow Balancing. The DRZC was able to detect the loss of one PBC unit, and kept using Steven's Croft loadbank as the only PBC unit available. 12. The current model prevents the island from being controlled effectively by the DRZC if the anchor generator is disconnected.

Outcome	GE Responsible	Customer Responsible (if applicable)
☑ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	Signature Date	Signature Date

4.7 Considerations about no-wind scenarios and tests run without the BESS

Some additional tests have been run to analyse the system's behaviour in case no WFs were available. In low and medium load scenario the majority of loads could be restored while respecting RoCoF and frequency thresholds, however the unavailability of priming function prevents the system from reconnecting one or two of the main loads. The number of loads that remain disconnected depends on setpoints of PBC units before the pick-up; this condition is not entirely predictable, as the system has multiple equilibrium points for each load scenario and is influenced by manual power reference setpoints applied at the generators. The recommendations for further work address considerations for narrower bands of operation and setpoint control of Proportional Regulation (frequency droop) units, which would reduce the variability in generation output for a given loading scenario.

If only Steven's Croft loadbank is present as PBC unit, and no WF is connected to the system, no main load can be re-energised in a high-load scenario without exceeding both RoCoF and frequency thresholds. One or two of the three main loads can be re-energised in such conditions in medium-load scenarios.

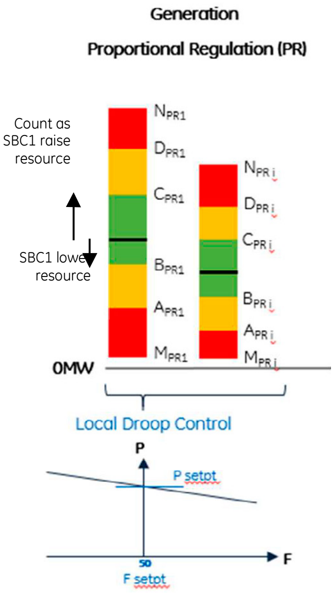
5 Further considerations and future work

The scheme was demonstrated in workshops between the partners and further developments considered. The following points describe further considerations and potential developments to refine the approach and prepare for a live implementation.

1. The anchor power setpoint defines the anchor output when the system is at 50Hz. The current process assumes that the power setpoint is applied manually by the plant operator and/or the control room operator. In the future, scenarios in which the power setpoint of the anchor generator is controlled by the DRZC could be considered; further discussions must follow, about how the power setpoint should be defined.

2. In a future development, the anchor generator (and other PR units) could also be counted as SBC1 dispatchable resource, where the resource available as SBC1 is the distance to the green/yellow boundaries. In this case, if the operating point is below threshold C, SBC1 raise should be made available, otherwise SBC1 raise capability should equal 0. Analogously, if the operating point is above threshold B, make SBC1 lower available, else SBC1 lower capability equals 0. In this proposed example, thus, DRZC will use the anchor generator consistently with the other resources in the system.

3. If both Power and Frequency setpoints are available, further work could analyse whether control of the frequency setpoint is useful. A possible application would be to set the zone frequency high prior to load pickup so that there is more headroom for frequency to drop during load pickup event. The current scheme aims to keep the frequency close to 50Hz. Further work would be needed to determine if a frequency setpoint would be valuable.



4. Confirmation of blackout situation should be communicated to all participating plants. This will result in them following a particular startup sequence, rather than restarting automatically and ramping up based on bus voltage. For example, blackout communication could happen though broadcast of Blackout triggered by operator's input of "Blackout Confirmation", where the signal is interpreted by devices as "Prepare for Restoration". For windfarms, this state would be auxiliaries connected but main LV breaker not connected, listening for command to start generating.

5. A small control adjustment and confirmation would be worthwhile when a unit becomes active in the control scheme. This would prove that the unit is successfully being controlled, and would exclude it and issue a warning if the confirmation fails.

6. In the current model, WFs send to DRZC a signal communicating the estimate of available power for generation. Communication of Power Available should be a requirement of all participating units, not just the wind power. Power Available can also serve as confirmation that the plant is ready.

7. Modes of operation for participating units should be clearly defined in service requirements.

8. In order to allow operators to work effectively on the blackout event, ADMS should clear a flood of individual alarms to highlight the underlying cause being a blackout, in a similar way to storm alarm management.

9. In the ADMS, a table of operating points of controllable elements and loads would be useful as drill-down. This table would include expected load pickup (cold load and steady state) for loads not currently connected.

10. In the ADMS, further validations can be considered as requirement to avoid automated switching closing a breaker when the system is not ready.

11. Initially, implementation should focus on load bank and anchor generator only. Limited grid-following windfarm capacity can be connected, and grid forming mode is important. Some simulations have been run according to this scenario; relevant limitations are highlighted in 4.7.

12. There is 2-3GW BESS planned in SPEN area alone; the potential use for distribution restoration should be considered in future work. State of charge will be a component of the resource available.

13. Operator perspective to be considered; the dashboard should be ideally simplified and made more intuitive, especially given that it is not supposed to be used by operators on a daily basis, but rather in highly unusual situations with very disturbed system conditions.

14. When the execution of a group telecontrol or automation program ends with errors, the user should be able to view and check these errors easily from the ADMS dashboard.

15. Due to fault level limitation, only ~8MW wind with grid-following control can be picked up in Dumfries & Galloway. This could be increased with a grid forming inverter mode. Where the power is limited, this should be reflected in the scheme configuration

16. Control options available from Aggreko load bank should be investigated. Further tests will be needed to confirm that the loadbank setpoint can be controlled continuously. If not, then further design consideration should be given to how it would be controlled.

17. Refinement of the fast balancing process would improve frequency performance. It may be possible to accelerate the event detection and increase the rate of rise of setpoint values. The process of holding and releasing response could be improved to avoid reducing the response

18. The response available to stabilize disturbances at a given time is significantly affected by the operating points of fast balancing resources. Care should be taken in choosing the threshold parameters, particularly the upper and lower levels at which slow balancing is triggered. A narrower target band may be beneficial compared with the thresholds used in the tests.

19. Further exploration of multiple contingency events would be beneficial, along with a definition of the most significant contingency events or sequences of events that the system should ride through.

20. The testing was applied with relatively fast-acting governor control (PR), such that the PR response was applied in a similar timescale to the fast balancing (PBC) response. In practice, it would be expected that PR would be slower to respond and a greater share of response would be taken by PBC. Testing with different generation and governor characteristics would be worthwhile to identify the sensitivities.

21. A detailed Failure Mode and Effect Analysis (FMEA) would be beneficial for the system prior to business-as-usual deployment.

22. Planning guidelines should be developed to determine the extent to which variable resources such as renewable generation, contracted sheddable load and BESS charge can be relied on to extend the blackstart capability of a zone. There will always be a core blackstart capability in a zone, and there is a very low probability of restoration being required in the most restrictive low generation / high loading scenarios. The possibility could be further mitigated by using contracted sheddable load to make use of diversity in resources.

Appendix A Load Pickup Capability

The load pickup or system loss capability in the DRZ is determined by the following factors:

RoCoF limits for loss of mains protection

Frequency limits

Inertia of the zone

Volume and speed of Fast Balancing response

Volume and speed of Proportional Regulation

The load pickup capability is determined both where the currently available PBC and PR resources are used, and for the case where the controllable resources are primed to maximise the increase of fast power response as load is picked up. The boundary of the response is shown in Figure 31.

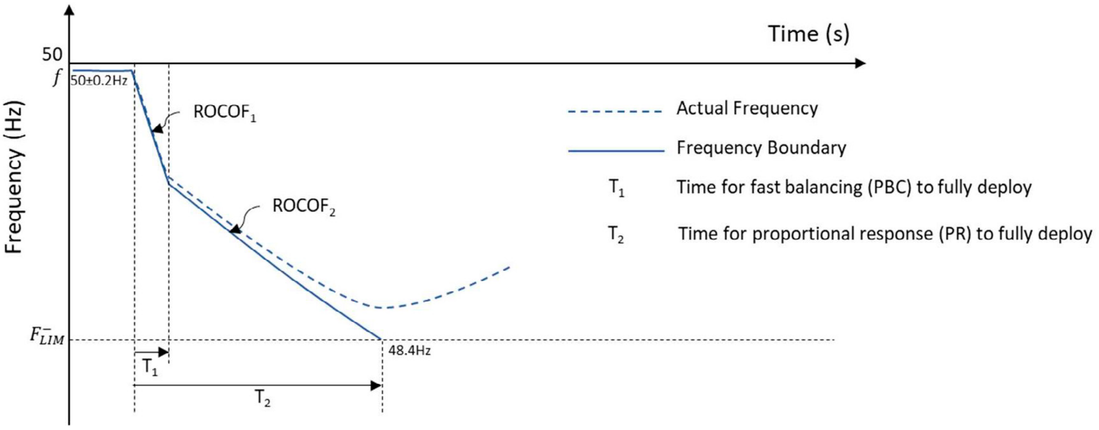


Figure 31 Boundary of frequency with load pickup and Primary Balancing Control (PBC) deployed

The initial RoCoF during time T_1 before PBC is applied is defined by the zone inertia and load pickup or loss.

$$\Delta P_L = H'_{zone} RoCoF_1$$

In the case of a load pickup, ΔP_L and RoCoF are both negative. The inertia H'_{zone} is expressed as shorthand in units of MWs^2 which directly relates a MW power imbalance to RoCoF in Hz/s, rather than the usual convention of expressing in units of MWs.

The expressions differ by a factor of $2/f_0=1/25$:

$$\frac{2H}{f_0} = H' \quad thus \quad \frac{H}{25} = H' \quad where\ H\ in\ MWs\ and\ H'in\ MW.s^2$$

It is assumed that the time for Fast Balancing (PBC) to respond is less than the time for G99 loss of mains relays to operate, which require the RoCoF signal magnitude to exceed 1Hz/s for at least 0.5s. The loss of mains relays also have a relatively long window to calculate RoCoF, so the time available is close to 1s.

Criterion 1: Maintain RoCoF within Loss of Mains trigger level

Once PBC responds, the power imbalance is offset by the power provided by the total positive PBC response, which can be any value up to the positive PBC margin, $\Sigma\Delta\mathrm{PBC}^{+}$, thus for the second RoCoF period, the slope is no steeper than the RoCoF given by:

$$\Delta P_L + \Sigma\Delta\mathrm{PBC}^{+} = H'_{zone} RoCoF_2$$

In this equation, ΔP_L is negative (increased load) and is offset by the positive increase in power to the grid from batteries and/or reduced load from a load bank, $\Sigma\Delta\mathrm{PBC}^{+}$. With sufficient resource available, this response would balance and RoCoF$_2$ would become zero. If there is not sufficient PBC margin to balance the load loss, it will reduce the RoCoF. The limit value of ΔP_L is where the remaining imbalance after PBC response causes a RoCoF that is inside the permitted value $RoCoF_{lim}^{-}$ and is balanced by the further action of Proportional Regulation (PR) before the frequency crosses a load shed limit.

$$\Delta P_L \geq -\Sigma\Delta\mathrm{PBC}^{+} + H'_{zone} RoCoF_{lim}^{-}$$

Since ΔP_L and $RoCoF_2$ are negative values for load pickup, this shows that a larger load pickup is possible when PBC is deployed.

The load shedding case is similar, but with the power imbalance positive (excess generation), RoCoF positive and PBC negative (reducing power to the network). In this case, the maximum excess power is limited by:

$$\Delta P_L \leq \Sigma\Delta\mathrm{PBC}^{-} + H'_{zone} RoCoF_{lim}^{+}$$

Criterion 2: Load pickup must be smaller than the total balancing control capability (PR+PBC)

In the case where PBC alone cannot balance the power in the zone, the total response that can be delivered through PR and PBC must be larger than the load loss, otherwise the zone will not reach a balance. Thus, the limit value, ΔP_L, which is negative for a load pickup, must be within the total margins of control of the PR and PBC resources to add generation to the island:

$$-\Delta P_L \leq \Sigma\Delta\mathrm{PR}^{+} + \Sigma\Delta\mathrm{PBC}^{+}$$

Criterion 3: Frequency should not violate level limits

Assuming the continuous operation of frequency is within +/- 0.2Hz of nominal 50Hz, and the frequency change must be kept within F_{lim}^{-} and F_{lim}^{+}, the largest downward frequency excursion is $(49.8 - F_{lim}^{-})$.

$$F + RoCoF_1 . T_1 + RoCoF_2 . (T_2 - T_1) \geq F_{lim}^{-}$$

Where F is the starting value of frequency (49.8Hz as a conservative value)

T_1 is the time for PBC to respond

T_2 is the time for PR to fully respond

Replacing the RoCoF terms with load pickup, PBC and inertia:

$$F + \frac{\Delta P_L}{H'_{zone}} . T_1 + \frac{\Delta P_L + \Sigma\Delta\mathrm{PBC}^{+}}{H'_{zone}} . (T_2 - T_1) \geq F_{lim}^{-}$$

Rearranging

$$\frac{\Delta P_L}{H'_{zone}}.T_2 \geq -\frac{\Sigma\Delta\mathrm{PBC}^{+}}{H'_{zone}}.(T_2 - T_1) + (F_{lim}^{-} - F)$$

$$\Delta P_L \geq -\frac{(T_2 - T_1)}{T_2}\Sigma\Delta\mathrm{PBC}^{+} + \frac{H'_{zone}}{T_2}(F_{lim}^{-} - F)$$

Replacing F with 49.8Hz as the conservative limit of normal steady-state frequency operation:

$$\Delta P_L \geq -\frac{(T_2 - T_1)}{T_2}\Sigma\Delta\mathrm{PBC}^{+} - \frac{H'_{zone}}{T_2}(49.8 - F_{lim}^{-})$$

To determine the acceptable load pickup value, the three criteria must be evaluated and the most conservative value of load pickup value used, which is the smallest absolute value of ΔP_L in the limiting cases. This value is the same as the largest generation loss case. A similar approach can be used to find the largest load loss capability, but using the lower limit values of the controllable resources, positive RoCoF limits, and upper frequency bounds.

Appendix B Restoration Path

The general aim of the restoration sequence is to maintain sufficient resources and margins for the island to be robust against unexpected load pickup values and unplanned trips during the process. Also, there is an advantage to restoring customers early, but not at a risk to the stability of the island and its capability to absorb disturbances. Therefore, it is useful to interleave generation and load pickup.

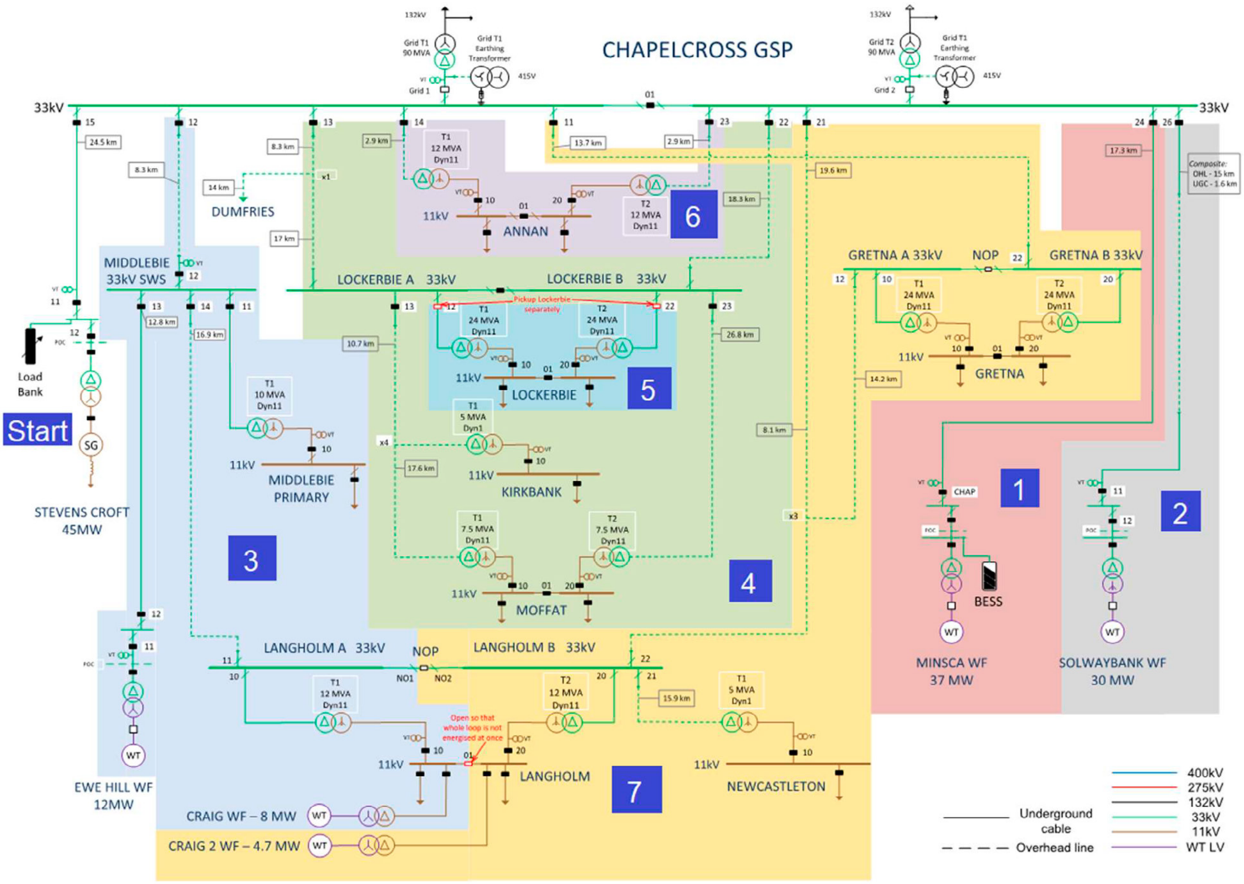


Figure 32 Restoration Blocks

Table 8 Net Load and Generation Ranges in Restoration Sequence Blocks

		P MW			Q MVAR		
Sequence		MAX	MEDIAN	MIN	MIN	MEDIAN	MAX
1	MINSCA WF (excl. BESS)	**37.00**	14.80	-1.85*			
2	SOLWAYBANK WF	**30.00**	12.00	-1.50*			
3	MIDDLEBIE	0.00	-2.49	-5.15	-0.64	-0.29	0.00
	LANGHOLM A	2.88	0.02	-5.23	-0.91	0.05	1.88
	EWE HILL WF	12.00	4.80	-0.6*			
4	MOFFAT	0.00	-2.05	-2.11	-2.05	0.00	-3.74
	KIRKBANK	0.00	-0.87	-0.91	-0.87	0.00	-1.88
5	LOCKERBIE	-4.62	-9.11	**-14.81**	-4.05	-1.60	0.23
6	ANNAN	-2.89	-5.87	**-11.23**	-1.74	0.04	0.86
7	LANGHOLM B	2.42	-0.44	-6.59	-0.69	0.16	1.41
	GRETNA	0.00	-3.34	-6.70	-1.18	-0.29	0.11
	NEWCASTLETON	0.95	0.50	0.00	0.00	0.04	0.12

* Windfarm startup loads assumed to be 5% of rated capacity, e.g. -1.85MW for Minsca. Median is 40% of capacity.

Assumptions:

- Anchor generator can regulate between 10-45MW; initial condition is mid-range (30MW) balanced by 30MW on load bank.
- Load bank capacity is 35MW
- Assumptions for windfarm at 33kV or above
  - Load of -5% of their rated capacity is drawn at startup before they can supply power.
  - Minimum operating limit of 10% of rated capacity is required to maintain operation. At startup, the windfarm ramps from -5% to 10% setpoint once the plant is ready.
  - The DRZC will use the Power Available signal from the windfarm to indicated when >10% power is available from the windfarm.
  - Windfarm median generation capacity is 40% of their rated capacity.
- Negative values indicate net load from the demand statistics, and positive values indicate net generation.
- Cold load pickup (CLP) will include load but not generation, as the generation will come online after 20s for LV DER, and possibly longer for 33kV connected DER. Cold load pickup will therefore be estimated conservatively from the table above as 1.5x largest negative value. Some refinement may be possible in future to use stored values to estimate load pickup with less conservatism.
- Steady-state load (SSL) value
  - High load: largest negative value (MIN)
  - Normal load: median value
  - Low load: largest positive value (MAX)
- High load values will be used unless another value is required for specific cases

Load and Windfarm Profiles

Given the above assumptions and the use of the high load values, the load profiles are assumed to be as shown in Figure 33 and Figure 34.

A startup profile for P&Q is assumed to represent the initial load as the windfarm is connected to the system and picks up output. Once the bus is energised, there is a short delay with zero power until the windfarm commences its startup when it draws a small load. Once the startup sequence is complete, the unit will ramp to its minimum operating level.

A "power available" limit value is applied which varies over time with similar characteristics to the expected variation of wind. Power Available is an external signal to the DRZC, provided by the windfarm operator. It is assumed that this will be zero before and during startup, rising to equal the minimum operating level once the startup sequence is complete. Once the plant is ready to ramp up generation, Power Available will be updated to indicate the maximum dispatchable power.

In Figure 33, the load profile is shown with CLP reaching 1.5x the maximum load condition. LV generation starts to pick up at 20s and is largely operational in a further 3 minutes. This accounts for an assumed 60% of the difference between CLP and steady-state operating value. The remaining 40% of the transition completes after about 30 minutes.

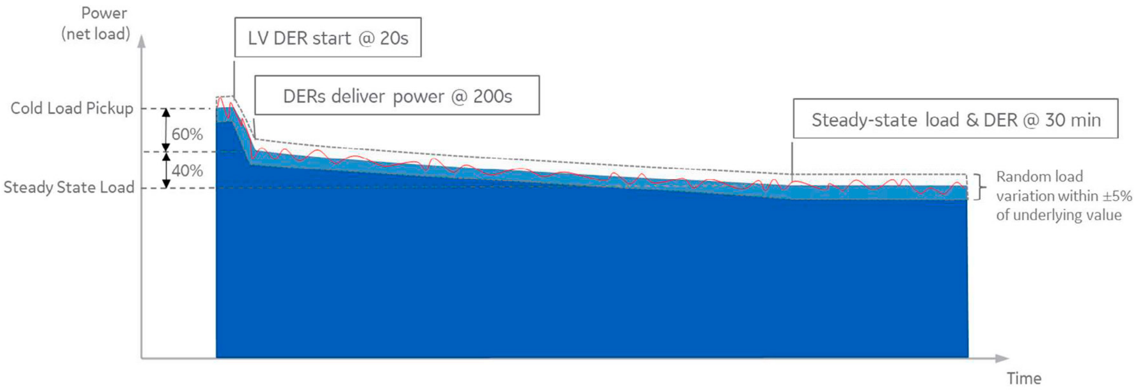


Figure 33 Load profile for primary with mixed demand and DER

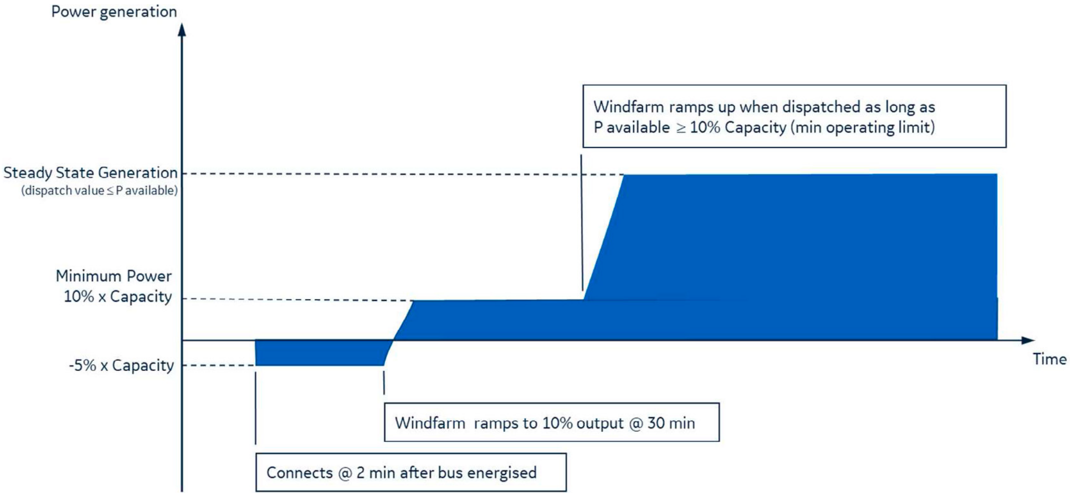


Figure 34 Generation profile for Windfarm startup at 33kV or above

Restoration Sequence

Start Anchor generator at mid-range (27MW), balanced by load bank.

Windfarms energized first to start process of returning online. It may take some time to start generating, so it is useful to start as soon as possible.

1. **Minsca WF + BESS.** In order to increase controllable resources including both PBC and SBC1, the windfarm with BESS attached is energised early in the process. Initial power to start can be supplied by anchor.
2. **Solwaybank WF.** Energise Solwaybank to increase SBC resource.
3. **Ewe Hill WF / Middlebie / Langholm A**. Includes both generation and load. Maximum cold load pickup is 15.6MW (1.5x 10.4). This can be balanced by the load bank (PBC) and does not rely on other generation. Langholm A energises Craig WF, and therefore increases generation resources. Picking up a small/medium load early in the process improves the stability and margins of the system without exposing the anchor to a large disturbance.

Loads will be picked up by starting with a small load, then larger loads in the middle of the sequence, and the final step includes a load which can be manually split to smaller blocks if the cold load pickup is too large.

4. **Moffat, Kirkbank.** Final small load pickup, with maximum cold load pickup of 4.5MW (1.5x 3.0)
5. **Lockerbie.** The largest load in the Chapelcross system, the maximum cold load pickup is 22.2MW (1.5x14.8). At the high load end, this would require some generation from windfarms in addition to the anchor generator.
6. **Annan.** The second largest load in the Chapelcross system, the maximum cold load pickup is 16.8MW (1.5x11.2).
7. **Langholm B, Gretna, Newcastleton.** This stage includes both load and generation and if there is insufficient controllable resource to pick up the group as a whole, the operator can manually pick up the primaries separately. The normal cold load pickup is 10MW according to the rule above, and maximum cold load pickup is 20MW (1.5x13.3).

Restoration Sequence Validation

The loading of the controllable elements during the proposed restoration sequence is reviewed in Table 9 and Table 10. This shows that the restoration sequence is viable. A number of interventions of fast and slow balancing are expected in both cases.

Table 9 and Table 10 give indicative snapshot values of the balancing through the course of restoration. In Table 9, the restoration is illustrated using the maximum loads expected (see Table 8) to define both the cold load pickup as 1.5x the maximum load, and the steady-state value. In Table 10, the restoration is illustrated using the median load values for steady-state, but with the same cold load pickup value of 1.5x the maximum load is used as in Table 9.

Table 9 Example of Island Balancing with load settling to High Load Condition

	Start	Block 1	Block 2	Block 3	Block 4	Bk3&4 Load settling	Block 5 Priming	Block 5	Minsca WF Gen Start	Minsca WF Gen Ramped & Bk5 settling	Frequency adjust PBC	Block 6	SBC Adjust	Solwaybank WF Gen Start	Block 7 Priming	Block 7	Frequency adjust SBC	Bk 6&7 Load settling	Frequency adjust PBC
Time (min)	0	1	2	3	4	34	35	36	37	66	67	67	68	69	70	71	72	100	101
Anchor	30	31.8	33.3	33.5	32.8	27.3	40	40	34.5	16	30	30	30	25.5	40	40	31	18.8	30
Load bank	-30	-30	-30	-14	-8.8	-10	-22.7	-8	-8	-8	-15	-6.6	-10	-10	-17	-7	-7	-7	-12.6
Minsca BESS	0	0	0	0	0	0	0	7.5	7.5	7.5	0.5	8.9	5	5	-2.5	7.4	7.4	7.4	1.8
Minsca WF	0	-1.8	-1.8	-1.8	-1.8	-1.8	-1.8	-1.8	3.7	14.8	14.8	14.8	22.1	22.1	22.1	22.1	22.1	22.1	22.1
Solwaybank WF	0	0	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	3	3	3	12	12	12
Ewe Hill WF	0	0	0	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Load block 3	0	0	0	-15.6	-15.6	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4
Load block 4	0	0	0	0	-4.5	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
Load block 5	0	0	0	0	0	0	0	-22.2	-22.2	-14.8	-14.8	-14.8	-14.8	-14.8	-14.8	-14.8	-14.8	-14.8	-14.8
Load block 6	0	0	0	0	0	0	0	0	0	0	0	-16.8	-16.8	-16.8	-16.8	-16.8	-16.8	-11.2	-11.2
Load block 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-19.9	-19.9	-13.3	-13.3

asdasd

Table 10 Example of Island Balancing with load settling to Median Load Condition

	Start	Block 1	Block 2	Block 3	Block 4	settling	Adjust PBC	Block 5	Start	Bk5 settling	adjust PBC	Block 6	Start	Priming	Block 7	adjust SBC	settling	PBC+SBC
Time (min)	0	1	2	3	4	34	35	36	37	66	67	67	69	70	71	72	80	81
Anchor	30	31.8	33.3	33.5	32.8	19.3	30	30	24.5	11.4	30	30	30	40	40	30	10	30
Load bank	-30	-30	-30	-14	-8.8	-10	-15.4	-5	-5	-5	-19	-5.3	-9.8	-14.8	-4.9	-10	-10	-20
Minsca BESS	0	0	0	0	0	0	-5.3	6.5	6.5	6.5	1.9	5	5	0	10	5	5	-5
Minsca WF	0	-1.8	-1.8	-1.8	-1.8	-1.8	-1.8	-1.8	3.7	3.7	3.7	3.7	3.7	3.7	3.7	14.8	14.8	7.3
Solwaybank WF	0	0	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	3	3	3	12	12	12
Ewe Hill WF	0	0	0	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Load block 3	0	0	0	-15.6	-15.6	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
Load block 4	0	0	0	0	-4.5	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9
Load block 5	0	0	0	0	0	0	0	-22.2	-22.2	-9.1	-9.1	-9.1	-9.1	-9.1	-9.1	-9.1	-9.1	-9.1
Load block 6	0	0	0	0	0	0	0	0	0	0	0	-16.8	-16.8	-16.8	-16.8	-16.8	-6.7	-5.9
Load block 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-19.9	-19.9	-10	-3.3

🟥 RED Outside Trim Level - initiates balancing action
🟨 YELLOW Margin for Trim Action to maintain
🟩 NORMAL Operating condition

Appendix C Communication Strategies Report

A.1 Introduction

This appendix specifies the communication strategies used in the designs for a Distributed ReStart solution. It describes a desktop-based study achieved by performing a penetration testing technique to the designs provided in Report 1, as shown below. The desktop study shall feed into the potential attack vectors for the proposed communications, networks, and data, highlighting the ways an attacker may exploit any entry point to the system. Protection and prevention mechanisms are discussed and mapped to the attack vectors to demonstrate the effectiveness of the designs in securing the data and systems.

The below diagrams show the network design for some of the key sites in the Distributed ReStart architecture, in which the desktop study for attack vectors was derived from.

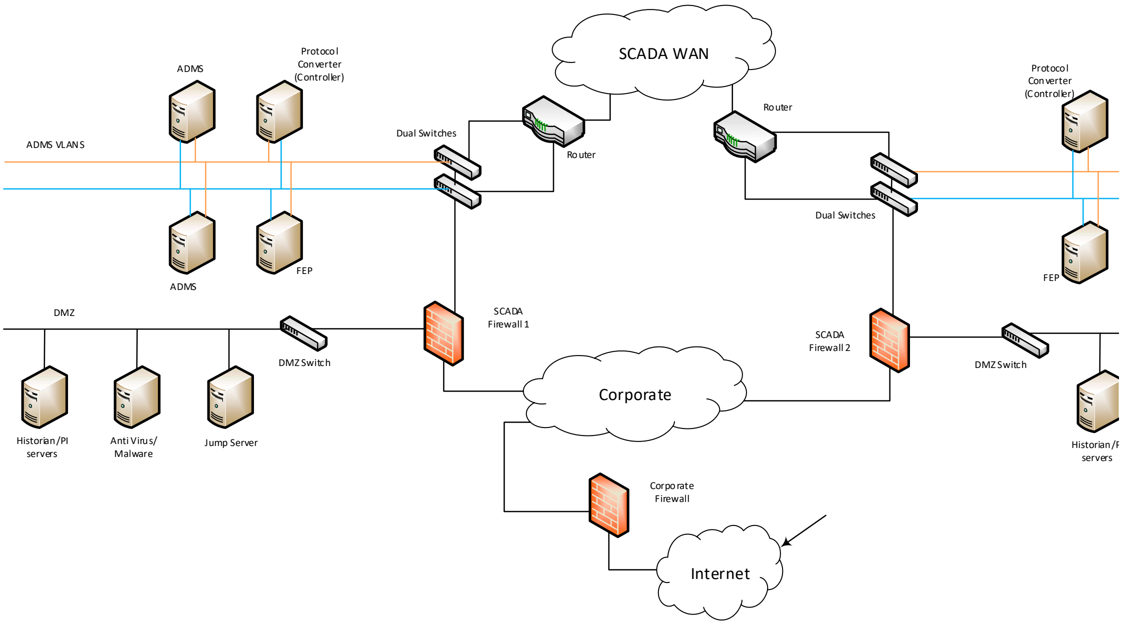


Figure 35 - Example DNO central control network architecture

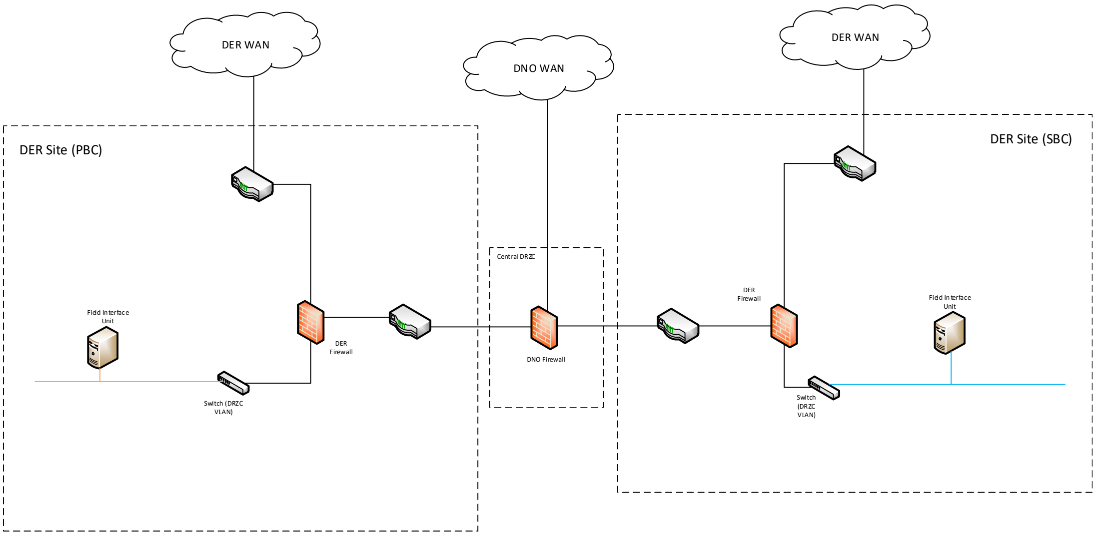


Figure 36 - Example of fast and slow balancing sites where multiple are available per zone

A.2 Overview Communications Design

The following section briefly discusses the communications design for Distributed ReStart, with a focus on cyber security requirements for the communication strategies.

The proposal for the protocols that will be required with in the Distributed Restart Network are as follows:

- ICCP
- IEC 60870-5-104
- C37.118
- DNP3
- IEC 61850-90-5 R-GOOSE

ICCP

The ICCP protocol will be used between DNOs and ESO for visualisation of the distribution network. ICCP does not provide encryption or authentication and instead should be secured in the lower protocol layers (i.e. via TLS or VPN).

IEC 60870-5-104

The IEC 60870-5-104 protocol specifies TLS for encryption and specifies application layer authentication of data packets using Message Authentication Codes (MAC).

C37.118

The C37.118 protocol should be encrypted using TLS and utilise mutual TLS with client certificate authentication to provide verification of identity of the client and server

DNP3

The DNP3 protocol should be encrypted using TLS, specifies application layer authentication of data packets using Message Authentication Codes (MAC).

IEC 61850-90-5 R-GOOSE

The IEC 61850-90-5 protocol provides encryption and authentication of data using symmetric keys issued from a central KDC (Key Distribution Centre)

A.3 Desktop Study - Penetration Testing Techniques

The following section presents a desktop study of the penetration testing techniques for the communications designs for Distributed ReStart. The design was reviewed from a security point of view using the following attack methods:

A.3.1 Network Attacks

The following network attacks could be exploited against the networks used to host and carry data for Distributed ReStart systems:

- Computer Virus / Worm

  Computer viruses are one of the most common network security attacks that can cause sizeable damage to your data on network.

  Computer worms are nothing but a malicious type of software that spreads from one infected device to the other by duplicating the virus. Their objectives by exploiting network vulnerabilities and gain access to devices.

- Man-in-the-middle

  MIM (man-in-the-middle) attacks are a type of cyberattack, black hats hijack the private communication intended between two parties. By intercepting the communication, the attacker tries to monitor and control their messages to either disrupt files, steal confidential data.

- Packet Injection Attack

  A packet injection attack is a common attack vector that hackers use to inject data into the packets on a network. This would allow attackers to change data while it is being transmitted to the devices.

- DoS (Denial of Service) and DDoS Attacks

  The difference between DoS and DDoS attacks is that hackers launch DoS attacks through one host network. DDoS attacks are more sophisticated, and attackers can use several computers to exploit targeted systems. Since the attack is launched from several compromised systems, it's hard to detect and protect from DDoS threats.

A.3.2 Protocols Attacks

The following protocol attacks could be exploited against the protocols used by Distributed ReStart systems:

- Man-in-the-middle

  MIM (man-in-the-middle) attacks are a type of cyberattack where black hats hijack the private communications intended between two parties. By intercepting the communication, the attacker tries to monitor and control their messages to either disrupt files or steal confidential data.

- Packet Injection Attack

  A packet injection attack is a common attack vector that hackers use to inject data into the packets on a network. This would allow attackers to change data while it is being transmitted to the devices.

A.4 Strategies

The following section summaries the security design choices and associates the protection mechanisms with the desktop study in the previous section, highlighting how each attack is mitigated using the strategies in the designs.

A.4.1 Communication Strategies

Control Centre to DRZC Site

This comms requires power resiliency for the DRZC to send critical RTU measurements, breaker statuses, load pickup values and alarms to the ADMS. The ADMS is also required to send some breaker controls to the DRZC. Low latency is not fundamental for this comms as there is no requirement for fast response control.

This means the following communications mediums are viable options:

- Fibre
- Microwave Radio
- 5G
- 4G
- 3G
- VSAT

DRZC Site to Proportional Regulation Site[s]

This comms requires power resiliency for the DRZC to send setpoints and breaker control to the Field Interface Units located at PR sites. PR sites are required to send RTU measurements and breaker statuses to the DRZC. Low latency is fundamental for this comms as PBC resources may be co-located with the anchor generator and would require fast-balancing responses. However, where PR sites do not have PBC resources co-located, critical measurements from PMUs are still required by the DRZC, so there is still a need for low latency.

This means the following communications mediums are viable options:

- Fibre
- Microwave Radio
- 5G

DRZC Site to Primary Balancing Control Site[s]

This comms requires power resiliency for the DRZC to send setpoints and breaker control to the Field Interface Units located at PBC sites. PBC sites are required to send RTU measurements and breaker statuses to the DRZC. Low latency is fundamental for this comms as there the site contains fast-balancing resources that require fast response times for control.

This means the following communications mediums are viable options:

- Fibre
- Microwave Radio
- 5G

DRZC Site to Secondary Balancing Control Site[s]

This comms requires power resiliency for the DRZC to send setpoints and breaker control to the Field Interface Units located at SBC sites. SBC sites are required to send RTU measurements and breaker statuses to the DRZC. Low latency is not fundamental for this comms as there is no fast-balancing resources and instead bring slow dispatch loads into the DRZC power island.

This means the following communications mediums are viable options:

- Fibre
- Microwave Radio
- 5G
- 4G
- VSAT
- 3G

A.4.2 Network Strategies

The network designs highlighted in Report 1 includes protection against the attacks shown in the network and protocol attacks sections.

Firewalls and Segregation

The firewalls will have Internal, External and Demilitarised Zone (DMZ), this is protecting the access to the different areas across Distributed ReStart solution as shown in the design. Ingress can limit the number of packets received in a time range to protect against DoS/DDoS attacks while also blocking requests from unknown hosts. An external attack will be required to traverse through multiple layers of firewalls and security zones to reach the designated target. This also helps limit the spread of viruses.

Jump Servers with Strong Authentication

Protects from unauthorised access to the Distributed ReStart and critical control systems. Jump servers should be located in secure locations like a DMZ, giving the firewalls the ability to restrict access. Strong authentication protects against unauthorised access by attackers to the systems and the use of strong authentication (e.g. multi-factor authentication) protects the systems from password cracking attacks and entry into the systems.

Anti-Virus/Anti-Malware

Detection of viruses before they are deployed is one of the most effective ways to protect the networks. Malware and viruses are the most commonly used attack vector in ICS environments, so anti-virus/malware software is essential. Scanning all traffic within the Distributed ReStart networks and systems ensures that viruses are captured and can be contained before causing disruption to normal operation. Anti-virus/malware require internet access to update with new virus signatures, so a DMZ should be used to restrict the traffic flow to the OT network, and signatures can be pushed to offline AV servers for up-to-date scanning of the critical Distributed ReStart systems.

IP/MAC/CA whitelisting

The devices used on the Distributed ReStart network will use IP/MAC/CA whitelisting, this will ensure only the devices that are approved on the network are allowed to access. For critical systems, CA whitelisting should be used to mitigate against IP and MAC spoofing attacks. Any form of whitelisting will protect the networks from attackers deploying unauthorised devices to either mimic control devices, flood the network or perform local hacks that otherwise cannot be exploited remotely. These are especially important for unmanned sites (e.g. DER sites or DNO substations) where physical access to the network equipment is more likely.

Sandboxing Environments

Sandboxing environments help with protecting against viruses or malicious code entering a live environment and spreading to Distributed ReStart and critical systems when applying patches, updates or changing configurations. Patches for software may be susceptible to MiTM attacks where an attacker changes the patch to contain malicious code that is used to infect a network or system when applied. While checksums and hashes can protect against these types of attacks, the use of sandboxing environments act as a last defence mechanism to ensure that malicious code or viruses do not enter production/live environments. This should be used for all Distributed ReStart system patches, updates, training and configuration changes.

Network Isolation

Network isolation mechanisms are typically built into Next Gen Firewalls and can automatically restrict the flow of data between zones, essentially isolating a network or system from the rest of the infrastructure. This aids in reducing the spread of viruses; when a system is compromised and the anti-virus detects unusual activity, it can send signals to the NGFW to isolate the network to contain the virus. Manual intervention is typically required to re-join networks once the compromised system/network is fixed.

Mutual TLS

Mutual TLS not only verifies the authenticity of the host, but also the authenticity of the client. Just as standard TLS, the public keys of the host are used to encrypt data in transit which the host can decrypt with their private key. This encryption protects against sniffing attacks and packet injection attacks. The addition of the client and server authentication using their digital certificates allows each connecting party to prove their identity, protecting the systems from Man-in-The-Middle attacks or unauthorised users trying to communicate with Distributed ReStart systems.

A.4.3 Protocol Strategies

The following protocols have security built in by design:

- IEC 61850-90-5 R-SV
- IEC 61850-90-5 R-GOOSE

The security mechanisms provided by IEC 61850-90-5 R-GOOSE/R-SV enable each message to be encrypted and authenticated between hosts, protecting every message from sniffing, packet injection and MiTM attacks.

The following protocols do have security built in by design and will be encrypted using Mutual Transport Layer Security (mTLS), ensuring the data does not get tampered with between devices:

- IEC 60870-5-104
- DNP3
- C37.118

Mutual TLS as described in the previous section protects against sniffing, packet injection and MiTM attacks. Therefore, due to the lack of inherent security controls developed into the protocols, this is required for these protocols to protect the data while in transit between Distributed ReStart systems and networks.

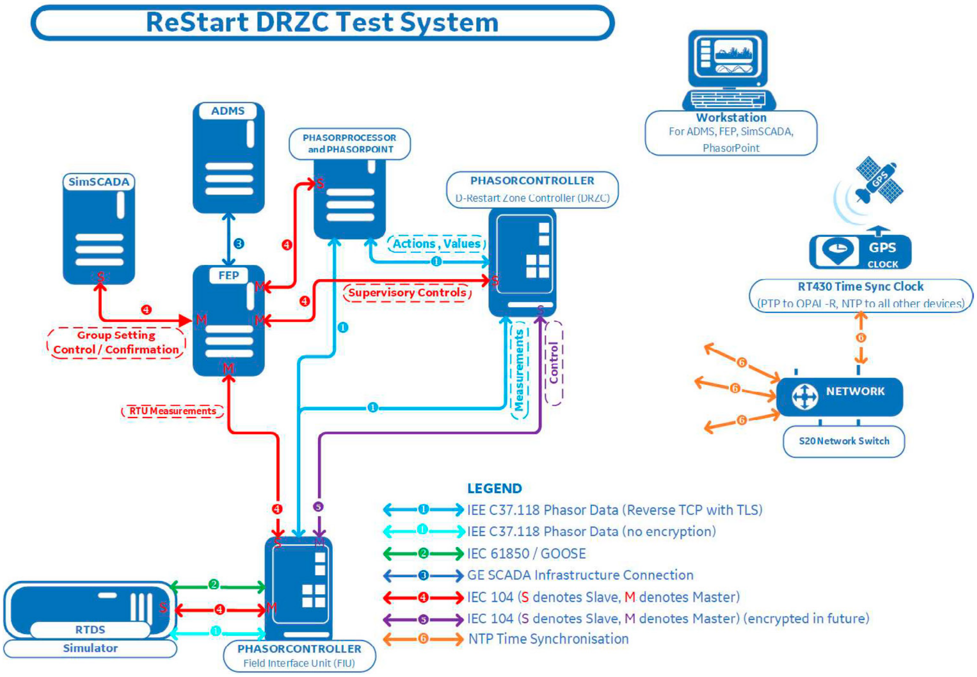
Certificates

As some of the protocols do not support end to end encryption, mTLS encryption will be used between devices using an internal certificate authority to generate client certificates to ensure the communication is encrypted on the network.

Appendix D Cyber Security Testing of HVDC environment

A.5 Overview

This document provides the preliminary high-level scope for the test strategy proposal carried out by Pen Test Partners. NG/SPEN shall review and provide input on current security testing to combine with the methodology in this document to form a complete test strategy proposal at a later date. The following test network is required to be tested as part of the Distributed ReStart project. The test system is deployed in the GE Edinburgh office for FAT and later replicated on hardware for deployment in the HVDC centre.



Distributed ReStart FAT system

A.6 Scope

Pen Test Partners recommend that the following tasks are carried out against the Restart DRZC Test network:

- Infrastructure Testing
  - Restart DRZC Test system
    - Un-auth Scans
    - Auth Scans
- Application Testing
  - Phasor Controller
    - Web Interface
- Configuration Review
  - Phasor Controllers
  - Phasor Processor

    - Workstation
    - FEP
    - ADMS
- Network Protocol to review:
    - Communication between Phasor Controller (FIU) and RTDS
    - Communication between Phasor Controller (DRZC and FIU) and FEP
    - Communication between FEP and ADMS
    - Communication between Phasor Controller (DRZC) and Phasor Controller (FIU)
    - Communication between FEP and SimSCADA
    - Communication between Phasor Controller (DRZC and FIU) and Phasor Processor
    - Communication between Phasor Processor and FEP
- PhasorController Hardware Review

A.6.1 Internal Infrastructure Testing

Internal testing will assess the Restart DRZC Test network landscape, identifying issues on network and workstations as well as network devices that could be used to gain system level access.

To include but not limited to the following:

- Vulnerability Assessment (VA) of internal network/s
- Focus on critical systems and platforms
- Manual testing to identify further obscure security issues and remove false positives

A.6.2 Application Testing

The Phasor Controller web application will be review against the Open Web Application Security Project (OWASP) methodology as show below top 10:

Injection Vulnerabilities: Such attacks attempt to inject code into the application that is processed, either by the web server, middleware, or database servers. Injecting SQL statements, operating system commands, and so forth can lead to a compromise of the underlying operating system or exposure of data.

Broken Authentication and Session Management: For an application with any form of individual user account, authentication and session management is critical in ensuring users only have access to their data. Being able to subvert such mechanisms means a user may be able to access other users' data or move upwards and access administrative functionality.

Sensitive Data Exposure: The lack of strict, robust controls around sensitive data can lead to it being exposed to an attacker. For example, not encrypting data in a database server could expose sensitive information if the application is vulnerable to SQL injection.

XML External Entities (XXE): The incorrect processing of XML data, or uploading malicious XML data, can lead to exploitation of vulnerable applications. For example, uploading a string within an XML document that attempts to access operating system information could lead to the compromise of that host.

Broken Access Control: Strict, robust access control ensures that a user cannot act outside of their area. If there are any issues with the access control, a user may be able to access data that should be off limits to them. For example, changing URL parameters that are not checked to see if the user has the relevant permissions – such as changing their user ID to that of another user.

Security Misconfiguration: This covers a multitude of issues, all relating to how the server and application are configured. For example, verbose error output that provides useful information to an attacker, sample applications that are vulnerable, directory listing not disabled. These flaws are numerous and can lead to a serious compromise.

Cross-Site Scripting (XSS): XSS has been an issue for a long time. A lack of input validation can allow an attacker the ability to inject JavaScript into the application that can target users in a number of ways. The three types of XSS: reflected, stored and DOM-based, can all be used to gather session cookies or other sensitive information.

Insecure Deserialization: Serialization of data is a method of simplifying data for easy storage or transmission. If an attacker can place malicious data within a serialized object, the endpoint that deserializes it may be exploited. For example, changing user ID and role data could lead to privilege escalation.

Using Components with Known Vulnerabilities: A web application is a complex amalgamation of numerous technologies. From the underlying operating system to libraries included from external sources, for example Google Maps, there are various components that make up the application. This increase the attack surface of the application, especially if out of date or vulnerable components are used. If the application is written with specific versions of libraries, it can be impossible to upgrade them in order to ensure the overall security of the application.

Insufficient Logging and Monitoring: Logging, monitoring, and the analysis of the resulting data is critical in understanding if the application has been compromised. Many attacks are noisy, such as repeated attempts to access a user's email account. However, unless logs are reviewed on a regular basis, such attacks can go unnoticed until sensitive data has been accessed.

However, reliance solely on a source such as OWASP will lead to missed vulnerabilities. As a result, we use a combination of our own experience, techniques and tools to produce a hybrid testing methodology. The testing process is driven by the application and how it functions. We look for logic flaws to see if the application can be exploited, chaining vulnerabilities to increase the efficacy of exploitation, and so forth. Due to the rich, and varied nature of web applications, we take an approach that combines frameworks such as OWASP with years of web application testing experience.

A.6.3 Configuration Review

A review of how the operating system is built and configured provides a picture of the security of the following devices:

- Phasor Controllers
- Phasor Processor and PhasorPoint
- Workstation
- FEP
- ADMS

Carrying out a review against best practice and identifying gaps that need to be addressed helps to improve the security of the device.

There are several overarching principles that are reviewed:

- Data at rest: Is sensitive data protected in the event of the theft of a device?
- Data in transit: Is sensitive data protected when being transmitted over networks? For example, are Virtual Private Networks used to ensure authentication of the user and encryption of the data?
- User security: How strong are user passwords? Does the system use multi-factor authentication? This is critical as a simple password could be the first step in a complete compromise of the environment. Can a standard user account be leveraged to gain access to a higher privileged account?
- Host configuration: Are the hosts built against a known and accepted standard? Are all hosts consistent with that standard?

A.6.4 Network Protocols to Review

The following PhasorController Communication will be reviewed:

Communication between Phasor Controller (FIU) and RTDS

Communication between Phasor Controller (DRZC and FIU) and FEP

Communication between FEP and ADMS

Communication between Phasor Controller (DRZC) and Phasor Controller (FIU)

Communication between FEP and SimSCADA

Communication between Phasor Controller (DRZC and FIU) and Phasor Processor

Communication between Phasor Processor and FEP

The following attacks will be conducted against the communications:

- Man in The Middle (MitM)
- Replay
- Tamper with the packets

A.6.5 Controller Hardware Review

The PhasorController device to be reviewed and to check what information can be retrieved from the device.

The testing will be conducted at Pen Test Partner’s lab (based in Buckinghamshire) and will require the availability of two devices. As part of this assessment, one of the devices will be tampered with, to the extent it cannot be reused safely.

PTP proposes to perform following hardware tests:

- General embedded Linux hardware test
  - covering physical attacks (serial, JTAG, chip-off) to recover firmware and any secrets from the device.
- Embedded build review

  - checking the extent to which the device has been appropriately hardened (services minimised, up to date, secure boot, firmware update mechanism).
- Using the information gained from the previous two stages, we would attempt to leverage this, to attack the platform more deeply e.g. use shared credentials to attack other devices or develop a malicious firmware update file.

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