Distributed ReStart

Energy restoration for tomorrow

DRZC Independent System Testing

Report by GE Digital

March 2023

In partnership with:

tnei

SP ENERGY NETWORKS

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Executive Summary

The Distributed ReStart project explores how distributed energy resources (DER), such as solar, wind, biomass, and hydro, can be used to restore power to the transmission network in the unlikely event of a blackout. While conventional black start involves a top-down approach of starting large generation, energising transmission network and finally restoring load, the bottom-up distribution restoration process involves starting and running zones of the distribution network, including customer loads, and energising up to transmission level. The project is led by National Grid ESO in partnership with SP Energy Networks and TNEI, with the participation of GE in the design, prototyping, and testing of a control system to manage the restoration of the zone.

The monitoring and control of a distribution restoration zone is complex, as it involves co-ordinated control of several resources with different technical characteristics within a zone to maintain power balance and stable frequency as load is restored. The system must also accommodate varying loads and renewable generation, and ride through unplanned disturbances while the network is in an unusual and fragile state.

The testing and validation of the monitoring and control system is an important element of successful deployment of distribution restoration zones (DRZs). The Distributed ReStart project explored methods of testing various aspects of the system. The learning obtained from the project is important for defining the process to qualify monitoring and control to co-ordinate the operation of a zone. Testing is required to confirm each part of the system, as well as the functioning of the whole scheme.

Distributed ReStart delivers learning on testing perspectives, processes, and required outcomes. The learning from Distributed ReStart helps to create the testing practices that are appropriate for further business-as-usual (BAU) roll out of the approach. In general, the testing process for BAU should be:

- **systematic** to prove the whole system performance
- **streamlined** for an efficient, repeatable, and standardised process
- **aligned** with project flow for zone deployment without holding up implementation.

Hardware-in-the-loop (HiL) testing proved to be very valuable in demonstrating and testing the overall system performance. HiL testing involves building a real-time dynamic model of the section of the power system in which the zone control will be applied. The real-time model supplies measurement data to the control devices and systems that would be used in the control scheme. Control signals are applied from the control system back into the HiL model, to show how the control applied by the scheme influences the operation of the zone. This allows observations and review of the performance of the power system with the zone control applied.

HiL testing was used both by GE for its system development and testing, as well as in the HVDC Centre for independent validation. While the principle of HiL testing was the same for both cases, the use of two different platforms and independently developed models is important confirmation of the robustness of the process and provides learning for further improvements. The two processes differ in terms of the model used and the test scenarios chosen.

It is significant that HiL testing was carried out both by the system developer (GE) and by an independent third party. In a transition to BAU, it is not expected that independent testing would be duplicated for every new zone, however there is value in having an independent facility that would provide services such as:

- benchmarking of performance of reference designs for typical networks in the GB system

- segmentation of the testing to prove interfacing between parts of the system, which may not be supplied by a single vendor, for example to test the interfaces and co-ordination between:
  - network management and switching in the SCADA/distribution management system (DMS)
  - power balancing and frequency control in the zone controller
  - local device control systems.
- an environment for training and demonstrations for stakeholders.

The main conclusions drawn from the HiL testing are summarised as follows:

1. Real-time hardware-in-the-loop testing is a necessary part of the testing process, as it enables the overall system to be tested in a closed-loop configuration. Many scenarios and events can be applied. It is also useful for demonstration and development of the system including the user interface and network control through the DMS.

2. Both vendor testing and third-party testing have a role in the validation and testing of DRZC schemes, and HiL testing is an important element in both cases. This study has illustrated both.

3. Development of stable and usable models in a HiL environment and linkage to the DRZC and DMS is a significant technical challenge. The time taken to plan and implement HiL testing is significant and should not be replicated unnecessarily. In the roll out to business-as-usual deployment of DRZC testing, it is recommended that a rigorous vendor testing process will suffice for repeating roll out of DRZC schemes with similar characteristics.

4. High-speed electromagnetic transient (EMT) simulation of waveform data (used in HVDC Centre's RTDS™) is more complex than dynamic 50 Hz simulation (used in GE's Opal-RT™ system). Power electronic instability is a risk in some zones, and should generally be addressed in control design, not in the DRZC real-time operation. The additional complexity, and consequently engineering resource of EMT simulation, can be useful for type-testing the system's resilience against power electronic instability, and for testing DRZC features to detect and respond to such issues. However, it would not be efficient to repeat such tests for roll out of every new zone.

5. Communications latency testing and its impact on the outcomes of the control process proved to be a valuable element of the investigation.

6. Practical outcomes from the testing included identification and resolution of some DRZC control stability issues as well as addressing the setup and configuration of communication protocols used in the system.

7. Third-party testing is valuable and should be applied in the following situations:
   - as a benchmark for reference of zones with similar characteristics of network and resources
   - for a new or significantly modified DRZC design compared with established designs
   - for development and refinement of specifications for DRZC systems
   - for interfacing between systems supplied by different vendors.

8. Third-party testing requires the active collaboration between the testing party and vendor. The vendor's know-how to build and configure the system is necessary for the testing to be meaningful, and also leads to technical exchanges to improve the system configuration and resolve problems.

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DRZC Independent System Testing Report

Version 0.2A

Report on the lessons learnt from the Distributed ReStart System Testing Process from the GE and HVDC Centre collaboration. The learning contributes to the testing and validation processes for a business-as-usual rollout of DRZC schemes. The report addresses the various roles of the DRZC system designer and third-party testing in establishing robust processes around distribution restoration in the GB network.

Change History

Document Version	Date	Comments
0.1B	15/09/2022	Initial working document for GE & HVDC Centre
0.2	25/02/2023	Draft release to Distributed ReStart project team including HVDC Centre project outcomes, additional context on DRZC process, extended Executive Summary and Conclusions and other textual revisions.
0.2A	28/02/2023	Introduction section added, so that Executive Summary can be moved to Distributed ReStart branded summary output.

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Glossary

Acronym	Description
ADMS /DMS	ADMS: Advanced Distribution Management System (GE product) combining Distribution and Outage Management Systems. DMS: Distribution Management System, generic term not related to a vendor product
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 (Fast) Balancing Control
PhC	Phasor Controller
PMU	Phasor Measurement Unit
PR	Proportional Regulation
PTP	Precision Time Protocol
RoCoF	Rate of Change of Frequency
SBC	Secondary (Slow) 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

This report describes the procedures and outcomes of testing, validation and demonstration of the distribution restoration control scheme. The distribution restoration approach uses a synchrophasor-based wide area control scheme to manage the balancing and reserves of the zone as the restoration island is established and progresses through the stages of energising, picking up load, running with security margins and eventually resynchronising to the grid.

Hardware-in-the-Loop (HiL) simulation is an approach to testing and validation in which a model of the power system is created that represents the complex dynamic behaviour of the power system with interacting electrical and mechanical components as well as the various control and protection systems acting within it. Real-time dynamic signals are generated that represent the measurements that would be observed in the live system, and these measurements are streamed to the wide area control system. Various scenarios and sequences of events can be generated in the model that represent the behaviour of the real-world system, and credible scenarios can be introduced that would represent the power system operating normally or being subjected to credible disturbances. The physical equipment of the wide area control system receives the data, process it, and applies the control outputs as it would do in a live implementation. The control outputs are fed back into the HiL system and linked to the models of the controlled plant.

Thus, the wide area control scheme can be tested with the full closed loop response included. Furthermore, the user interface and data archiving features that are available for the live implementation can also be used to observe and analyse the behaviour of the whole system including the wide area control.

In the Distributed ReStart project, two HiL environments were used for testing the control scheme. The first was used by GE using an Opal-RT™ real-time simulator designed for simulating and streaming synchrophasor data.

The project went on to demonstrate collaborative testing between the National HVDC Centre using the RTDS™ real-time HiL environment. While the testing approach was similar in principle, the National HVDC Centre's testing extended the learning in a number of ways:

1. The simulation engine in the RTDS system generates waveform data at a rate of several kHz, which is then used to create synchrophasor data at 50 samples/second. By contrast, Opal-RT™ system directly simulates 50 sample/second synchrophasor data. The RTDS™ includes representation of very fast dynamics and potential stability issues that are not represented in the lower update rate of Opal-RT. The value of the additional complexity of the RTDS models has various benefits outside testing the wide area control scheme, for example in protection assessment and power electronic stability, but fulfils a similar role to the Opal-RT in terms of wide area control system testing.
2. The work provided illustrated the collaborative approach between a system vendor and a third-party testing organisation.
3. Various aspects of testing were carried out in the National HVDC Centre that had not been applied in the GE laboratory tests. In particular, the impact of communication latencies was tested, leading to improvements in the system configuration for greater resilience to network delays.

This report describes the test environment, the test processes undertaken, results obtained, and the conclusions drawn. It provides insights into the testing procedures that would be relevant for a rollout of the distribution restoration control system in a business-as-usual context.

2. Distribution Restoration Zone Control System

This section provides the context of the control process and describes the categories of resources used in balancing the zone and stages of the restoration process.

The primary role of the PhC_DRZC is to manage the frequency and power balance of the island as it is energised, loaded, run as an island, resynchronised, and restored to normal operation. During a blackstart procedure, the island is operated in a low inertia state and frequency is very sensitive to changes in load and generation. There is inherent uncertainty in the volume of load picked up and the variations of load and renewable generation, combined with low inertia, leads to highly variable frequency. This is addressed by the DRZC which applies a supervisory control to apply fast actions to rebalance the system in response to load pickup and unplanned trips of load or generation, as well as slower balancing actions that keep the frequency close to 50Hz and maintains the operating points of frequency regulation and fast-acting control devices at levels where there is a margin for control in either direction. The DRZC manages the island operation up to and including the resynchronisation process.

The PhC_DRZC is capable of fast response, with a real-time update cycle of 20ms. There are four key processes performed by the PhC_DRZC:

Primary (Fast) Balancing Detects large RoCoF and frequency deviation events, translates to an island power imbalance and triggers a balancing action using the load bank and/or battery responses.

Secondary (Slow) Balancing & Priming Detects the primary balancing resources (anchor generator and/or the load bank / battery) encroaching defined margins for regulating the power balance of the island and initiates rebalancing of the resources so that the anchor generator and load bank / battery return within the margins. Priming involves biasing the operating points of controllable resources to maximise the island's capability to pick up larger loads.

In a BaU implementation, the function calculates the size of load pickup or other power balance disturbances that can be sustained, with or without priming and would initiate a priming process to bias the resources before a large load is picked up.

The DRZC will apply Slow Balancing when the margins for control of the fast balancing units are encroached. The automated action is dependent on plant operators making setpoint following capability available.

Islanding & Resync Identifies whether the network is in island operation based on angle and frequency difference measurements and enables or inhibits the island mode of operation of PhC_DRZC. A further function provides an indicator to inform the operator if the island can be resynchronised. It also reports whether the resynchronisation is successful, leading to restoration of grid connected operation.

There is a resynchronisation control capability to align the frequency of the zone to the external grid frequency, which may not be exactly 50Hz.

It is assumed that the breaker closure to resynchronise the zone to the grid will be done using a local synchrocheck relay which is armed from the control room via the DMS.

Resource Managing Tracks availability of resources according to the categories of positive / negative and Fast / Slow Balancing services, aggregates and distributes Fast and Slow Balancing commands to physical plants. Reports the aggregated capacities to the operator.

The controllable generation, storage, load bank and demand capabilities are resources for frequency control classified as follows:

Proportional Regulation (PR) e.g. synchronous generators with governor droop, BESS	Power is modulated according to frequency deviation measured locally. This is a function of the local control system, as “frequency droop” and is required to keep the frequency stable. However, the action can be quite slow as it depends on control of large prime mover equipment and can be supplemented by faster power balancing control.
Primary Balancing Control (PBC) e.g Battery Energy Storage Systems (BESS), load banks	PBC may also be triggered by the DRZC from larger frequency deviations resulting from multiple disturbances or ramping events that do not generate a RoCoF event. The frequency deviation translates to a power imbalance that is compensated by fast balancing using PBC resources.
Secondary Balancing Control (SBC1) e.g. renewable generation	There may be renewable generation in the system that is operated with a constraint during the island operation to avoid frequency and voltage rise. SBC1 resources are controlled to operating points at which the PR and PBC resources can run at operating points at which there is a margin of control to respond to a disturbance of the zone’s power balance.
Emergency Secondary Balancing Control (SBC2) e.g. customer demand (some of which may be contracted)	Load shed resources to be activated in the last resort to avoid disruption to customers. However, this can be used if there is no other way to maintain a balance with sufficient margin in the PR and PBC controllable elements to withstand a credible contingency. If a load is providing a contracted service, it may be prioritised over other non-contracted loads.

This system is designed to include several elements of each category of control. There must be at least one resource classified as PR and one as PBC to use in a DRZC zone.

According to the staged process defined in the Distributed Restart innovation project, the DRZC is mainly used for control in Stages 3 through 6. The anchor generator startup is monitored with phasor measurements, and once the anchor generator is established and operating in frequency regulation mode, the control processes are enabled and operate through the network energisation, load pickup and island running stages, as well as supervising the resynchronisation.

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

Stage 2 The anchor generator is started by a local process determined by the generator operator, monitored using phasor measurements using PhasorPoint to observe the stability in the startup process. PhasorPoint provides a status indicator to ADMS that is required for ADMS to allow the operator to proceed to the next stage. PhC_DRZC control functions of Fast and Slow Balancing are initiated at the end of Stage 2.

Stage 3a Network energisation is observed using the phasor measurement infrastructure. Voltage control for network energising is achieved with local control without control intervention from the PhC_DRZC. However, there is a risk of unplanned load or generation trips in the island during network energisation and the PhC_DRZC will maintain the power balance and control margins to maintain frequency stability through such events.

Stage 3b Automated load and generation pickup sequences are initiated by the operator. The PhC_DRZC triggers Primary Balancing Control (load bank/BESS) using the Fast Balancing approach to keep RoCoF and frequency within acceptable limits. Slow Balancing will follow up actions and redispatch between Secondary Balancing Control and the Primary Balancing Control to ensure control margin is maintained. Proportional Regulation margins are maintained indirectly through Slow Balancing control.

Stage 4 Island running requires frequency management processes to maintain a stable frequency and to ensure that sufficient regulating margin is available. During island running, load drift and renewable generation output change the balance of the island, resulting in the Proportional Regulation governor function at the anchor generator to change output. If the anchor generator output approaches the limits of its regulating capability, a rebalancing action is taken to adjust Primary Balancing Control (the load bank or BESS) if there is headroom, or Secondary Balancing Control (preferably DER dispatch; load trip if necessary). If a disturbance occurs during Stage 4, Fast Balancing can also be triggered if the event is severe, followed by Slow Balancing.

Stage 5 Resynchronisation requires angle and frequency differences to be measured at PMUs on each side of the resynchronisation boundary. An indicator is provided to the operator to show when the frequency and angle difference values are within the pre-set limits. Once the frequency difference is within limits, the operator can arm the synchrocheck relay. The operator can then observe whether the resynchronisation was successful or not, and if not, there is immediate feedback to improve the conditions for another attempt.

Stage 6 Once continued successful grid-connected operation is confirmed by PhC_DRZC (typically within around 10-15s), the anchor generator governor can be switched to constant power and Fast and Slow Balancing processes can be disabled. Any other changes such as restoration of grid-connected protection and earthing can be initiated by the ADMS once the successful synchronisation check is received.

3. Overview of Testing Procedures

The testing strategy of a distribution restoration zone involves several processes.

Overall Control System Performance Tests

The performance of the zone control is tested in Hardware-in-the-Loop using a set of test scenarios that represent the dynamic behaviour and events that could occur in the distribution restoration process. The system is tested in closed loop control configuration.

This testing confirms the whole wide area control system from ADMS, through the DRZC to the interface to controlled plant. It includes the control algorithms, configuration, and processes to maintain the stability of the zone.

The control system performance testing includes the communications infrastructure as well as the control schemes. As well as testing the behaviour while the monitoring and control system is healthy, it is possible to emulate failures and latencies in communication and control devices, which tests the graceful degradation of the system.

Field Interface Testing

A stage of testing is required for the measurement and control interfacing to the controlled plant. The hardware to be installed at the monitored and controlled sites include the PMUs, I/O interfaces, human interfaces, and local control logic for failsafe and resilience of the system.

This stage of testing includes the communication links between the controlled plant and the zonal and central systems.

The field interface tests will generally involve open loop testing and will not normally require HiL testing.

Physical Island Performance Tests in the Zone

Tests are required in the real power system to observe the performance and stability of the zone in island operation. The operational system tests of island operation and network energization carried out in the Distributed ReStart project demonstrate this form of testing in the Power Engineering and Trials workstream[1]. Enhancement of this testing would be beneficial for business-as-usual deployment, where the performance of the zone is evaluated with the DRZC control scheme active.

On-going Maintenance and Update Tests

Once a DRZC is installed, there may be needs for updates to the monitoring and control scheme. A process is needed for validating updates prior to deployment and confirmation of the updates and return to service.

On-going maintenance may require open-loop lab tests and/or hardware in the loop tests, depending on the functionality being updated and tested.

[1] Report download (nationalgrideso.com): “Demonstration of Black Start from DERs (Live Trials Report): Part 1”, December 2021

Cyber Security Testing

The overall scheme and its components are tested for vulnerability to cyber attack. This element is covered in a separate report[2], and is outside the scope of this document.

The focus of this report is on the overall control system performance tests, which is based on hardware-in-the-loop testing. HiL testing is also relevant for testing and validating scheme maintenance changes where it may affect the performance of the scheme.

[2] Distributed Restart Design Report (nationalgrideso.com): "Distributed ReStart Lot 2 – Design Phase: Final Report" December 2021

4. Hardware-in-the-Loop Testing

Hardware-in-the-Loop (HiL) testing is a valuable facility for evaluation of performance of a complex control system. The HiL environment runs a real-time dynamic model of the system where the control scheme will be applied. It provides the same measurements at the same data rate as would be observed in the real power system.

The control scheme is implemented on DRZC hardware as it would be applied in the real power system. The measurement data is streamed to the control system, which processes the data and returns the control signals that would be applied to the controlled equipment. The control scheme outputs are communicated back into the HiL environment, which applies the control signals to the models of the controlled devices. This means that the actions such as fast and slow setpoint changes, breaker opening/closing, and resynchronization are applied in the HiL model according to the commands coming from the external DRZC system.

This process will demonstrate whether the overall system with the wide area control applied responds sufficiently rapidly to prevent violations of pre-defined power system dynamic requirements and remains stable.

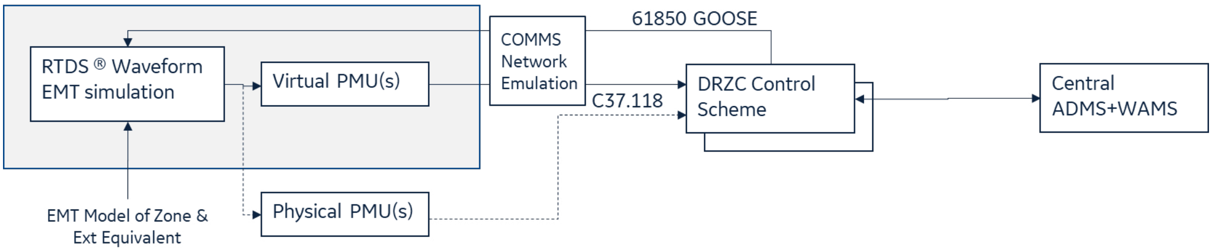
Various operational scenarios and sequences of events can be simulated in the HiL environment, testing the performance of the scheme in a wide variety of system conditions. There is much more freedom to design test scenarios to explore in HiL testing than could be tested in a real-life physical environment where the network conditions are very much more restricted and controlled.

Two variants of HiL test environments are outlined in Figure 1. The upper figure is representative of the HVDC Centre’s test environment using the Real Time Digital Simulator (RTDS). The lower figure is representative of GE’s Opal-RT Technologies platform.

The HVDC Centre’s implementation of the RTDS platform allows for testing a limited number of physical PMUs in the network as well as virtual PMUs that generate data in the same form as a physical PMU. In previous project work, consistency between physical and virtual PMUs was proven, and therefore only virtual PMU data was used in this case.

The GE implementation of the Opal-RT system uses RMS simulation with the ePHASORSIM software package, updating at 20 ms intervals. In this case, all PMUs are virtual and provide phasor data streams to the DRZC scheme. While there is software for electromagnetic transient (EMT) simulation with the Opal-RT system, this is not required for phasor-based control schemes and ePHASORSIM enables testing of larger systems.

Either HiL implementation can be linked with a SCADA/DMS (in this case the GE ADMS) which provides steady-state observability of the network state and interaction with control sequences provided by operators and/or automated switching sequences initiated by the ADMS. In practice, the link to input controls to the HiL platform uses IEC 61850 GOOSE messaging. Communication over IEC 60870-5-104 (including the ADMS control) is converted to IEC 61850 GOOSE so that controls can be applied to the HiL system.



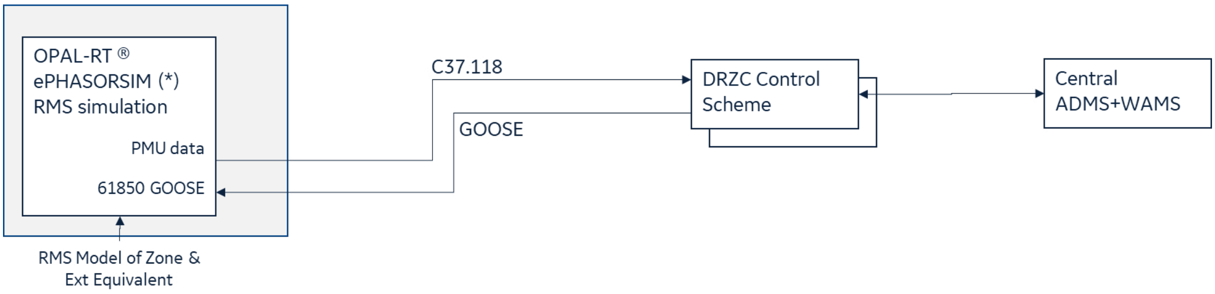


Figure 1 Examples of structure of Hardware-in-the-Loop test environments
(Upper: RTDS; Lower: Opal-RT)

4.1 Test Configuration

The system being tested is shown in Figure 2 and includes:

- Advanced Distribution Management System (ADMS) and Front End Processor (FEP) performing the network supervision and switching sequences
- PhasorProcessor PDC and PhasorPoint for visualization of synchrophasor data
- PhasorController DRZC managing the frequency stability and load balance of the island, with data and control links to the field interfaces and the central environment
- PhasorController FIU managing the interface between the DRZ scheme and the controlled plant (which is represented by the real-time simulator)

The real-time simulator can be either the RTDS™ simulator or the OPAL-RT™ simulator. In the practical tests, the RTDS™ simulator was used by the HVDC Centre for system validation, while the OPAL-RT™ simulator was used by GE for the development, testing and demonstration of the system.

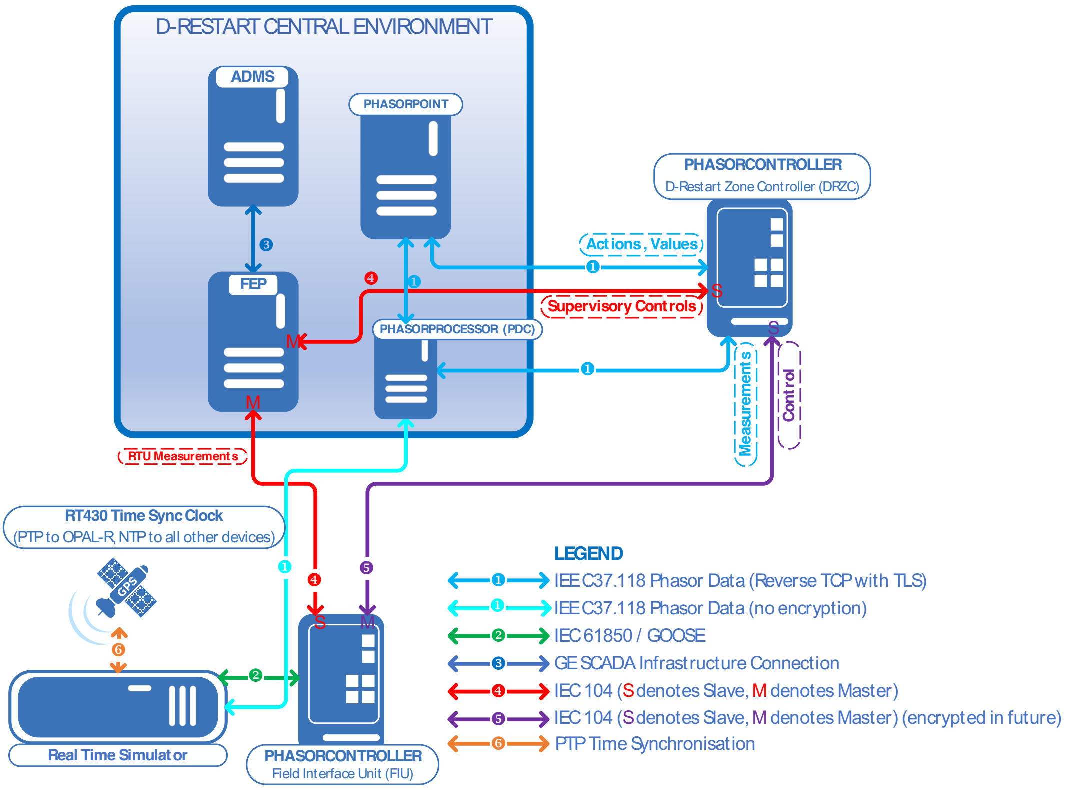


Figure 2 Test configuration for Hardware-in-the-Loop Testing

The test network was based on the Chapelcross distribution network with monitoring and control points as shown in Figure 3. The model represents the distribution network zone in detail, and where necessary includes a simple equivalent of the external system represented by an impedance and a high inertia synchronous generator.

The detailed implementation of the Chapelcross network differed between the RTDS and Opal-RT implementations. A detailed description of the Opal-RT modelling is provided in the earlier test report issued for the Distributed ReStart project[3].

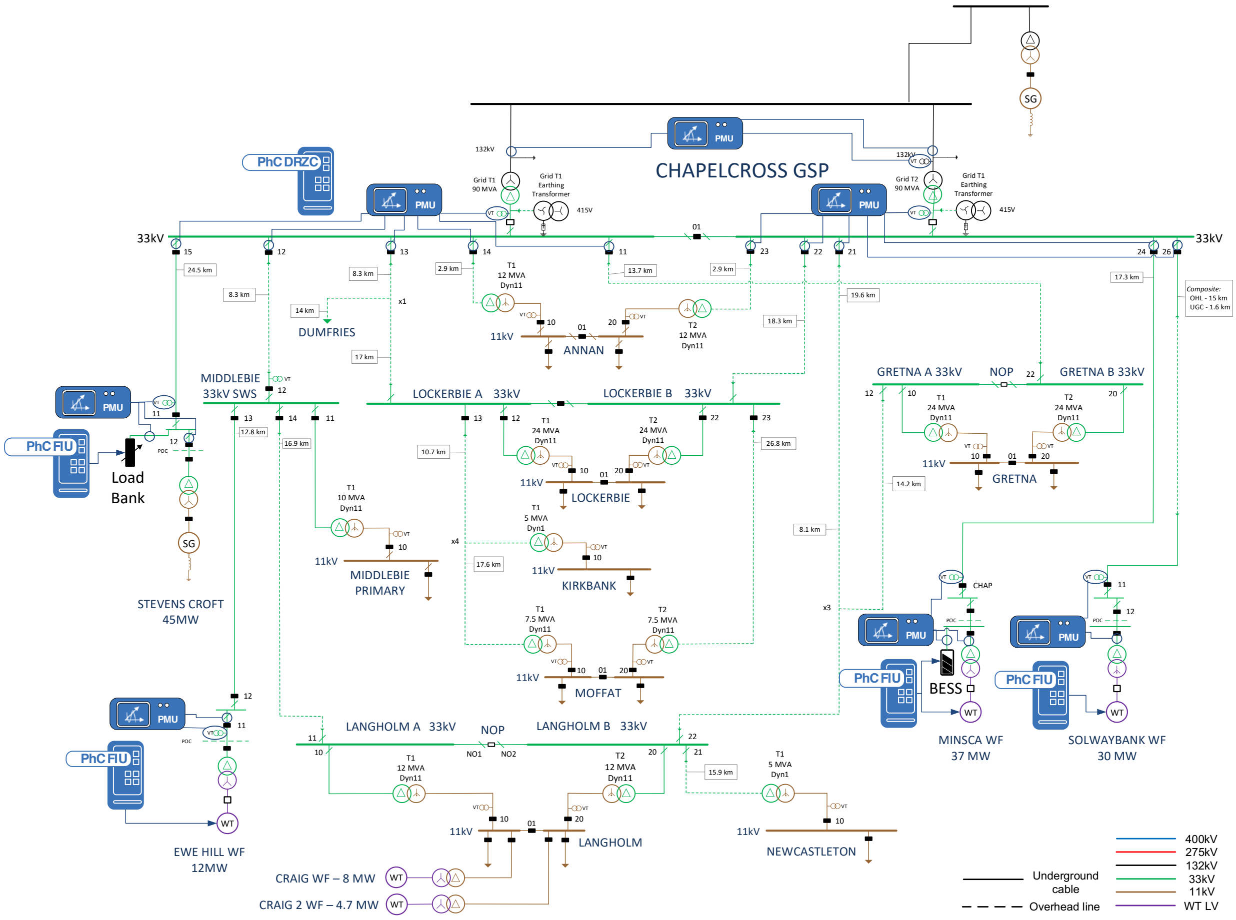


Figure 3 Chapelcross Distribution Network modelled for Distribution Restoration Zone Testing

3 "DRZC Factory Acceptance Testing 1 Report by GE Digital" download (nationalgrideso.com), April 2022

5. Results from Hardware-in-the-Loop Testing

5.1 Summary of Phase 1 HiL Tests on OPAL-RT™ Platform

The test process using the Opal-RT HiL platform successfully demonstrated the prototype DRZC controller, together with the SCADA/DMS system. The tests proved the capability to control the zone through the various stages of the blackstart process through to the eventual resynchronization to the transmission network. As described above, the tests were carried out using a model based on the Chapelcross distribution network.

The tests covered the stages of a distribution restoration process:

- Anchor generator start-up
- Network initialization
- Load pickup
- Power island balancing
- Resynchronisation
- Termination of island

The tests included various normal and disturbed scenarios to show how the DRZC responds in the planned restoration path as well as unplanned disturbance scenarios. The testing is described in detail in the report in terms of set-up, procedure, verification of outcomes and graphics illustrating the behaviour and dynamic performance of the zone with DRZC control.

The tests carried out in the Phase 1 procedure are listed in Table 1. The tests were all completed successfully and reviewed in stakeholder workshops. The detailed Phase 1 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.

Table 1 List of Acceptance Tests carried out in the Phase 1 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.

Test #	Functionality being tested
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

The Phase 1 testing, demonstration and workshop led to observations and insights on the further developments of a DRZC system. The following points are considerations for refining the approach in preparation for a live implementation.

1. The anchor generator power setpoint defines the anchor output when the system is around 50 Hz. 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. The anchor generator and other proportional regulation (PR) units could also be used as secondary balancing control dispatchable resource (SBC1) in parallel with the PR control function.

2. 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 50 Hz. Further work would be needed to determine if a frequency setpoint would be valuable.

3. Confirmation of blackout situation should be communicated to all participating plants including renewable generators. This will result in their following a particular startup sequence, rather than the normal automated process in which the restoration of bus voltage will initiate a process for startup and ramping up power. It is important to avoid excess power in the island as renewable generation ramps up, which leads to overfrequency and reduced margins to ride through disturbances.

4. 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.

5. In the current model, wind farms send to the 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.

6. Various enhancements of the SCADA/DMS operator were considered, such as:
   a. ADMS should clear a flood of individual alarms to highlight the underlying cause being a blackout, in a similar way to storm alarm management.
   b. 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.
   c. In the ADMS, further validations can be considered as requirement to avoid automated switching closing a breaker when the system is not ready.
   d. From the operator perspective, the dashboard should be simplified and 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.
   e. 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.

7. The potential use of battery energy storage systems (BESS) in distribution restoration should be considered in future work. State of charge will be a component of the resource available.

8. The use of wind resources is limited in the low short circuit capacity conditions of island running. This could be increased with a grid forming inverter mode. Where the power is limited, this should be reflected in the scheme configuration.

9. 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.

10. 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.

11. 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.

12. 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.

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

14. 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.

5.2 Phase 2 HiL Tests on RTDS™ Platform

5.2.1 Introduction

Testing at the HVDC Centre used the Real Time Digital Simulator (RTDS) platform, which executes full waveform EMT simulations in real-time as outlined earlier in Figure 1. In this instance, all PMUs required by the DRZC were implemented as virtual PMUs within the RTDS simulation environment.

A subset of the FAT tests was selected and repeated using the RTDS test up at the HVDC Centre. The first set of tests looked at the black start restoration to energise the 33 kV network from the anchor generator. The second set of tests looked at the effect of delays in communication on the fast-balancing control implemented in the DRZC. More focus and detail are provided on the fast-balancing tests with communications delays, as the results are new and provide fresh insight into the DRZC performance. In contrast, the black start tests are essentially repeated from the FAT tests [1] which have already been published.

5.2.2 Black Start

The HVDC Centre model of the Chapelcross 33 kV network was set up to simulate network initialisation after a black start event, and the subsequent island balancing as loads are picked up on the 33 kV network. Black start walkthrough tests for two different scenarios "High load, high power available" and "Medium load, low power available" were carried out corresponding to tests 5.00 and 5.01 listed in Table 1. Each scenario was taken through steps listed in section 1 (Network initialisation and Anchor start-up) and section 2 (Island Balancing and Load Pickup) of Table 1. Tests beyond section 2 were not repeated at the HVDC Centre as the RTDS model was not set up to simulate energisation of the 132/33 kV transformers or resynchronisation.

Tests showed that the GE controller behaved similarly at the HVDC Centre to previous FAT tests[1], with the controller successfully energising the 33 kV network, DER, wind farms and loads, and carrying out slow-balancing and fast-balancing control actions according to load and generation variations or events on the 33 kV network.

5.2.3 Fast-Balancing Control with Communication Delays

5.2.3.1 Model Configuration

The HVDC Centre model of the Chapelcross 33 kV network was set up to simulate fast-balancing events. In the model both Primary Balancing Control (PBC) devices, the Load bank at Steven's Croft, and the BESS at Minsca wind farm, were in service and controllable by the DRZC controller. The network was configured with the Stephen's Croft generator supplying the 33 kV network, with various distributed loads on the network, so that it was operating in the middle of its output range at around 23 MW.

The performance of the fast-balancing control in the DRZC was examined by repeatedly switching an additional 10 MW of load on and off and looking at the response, as the DRZC was subjected to various communications delays.

5.2.3.2 Communication delay test set up

The test setup at the HVDC Centre was shown previously in Figure 2. At the HVDC Centre the FIU, DRZC, ADMS, WAMS, FEP and GPS clock hardware were all physically located in the Protection Workshop. The RTDS hardware was located separately in the RTDS room, and the equipment was networked together as shown in Figure 4.

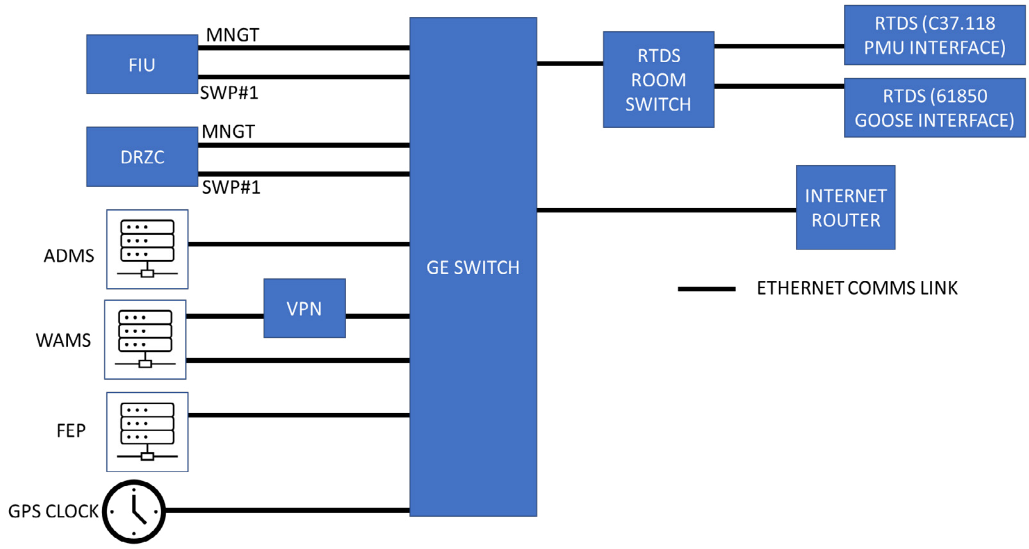


Figure 4 Communications/Network Setup at the HVDC Centre

Communications delays were introduced using the three test setups shown in Table 2. In each of the three tests, an Apposite Technologies 10G2 Network Emulator was used to introduce varying time delays until the fast-balancing control degraded. Further details on the communications test setup are provided in 8.Appendix A.

Table 2 Communications Delay Test Setup

Test	Link (Bidirectional)		Protocol
1	DRZC	FIU	IEC 104 encrypted
2	WAMS	DRZC	IEEE C37.118 with TLS
3	WAMS	RTDS	IEEE C37.118

5.2.3.3 Test Results

The first comms delay test, described as Test 1 in Table 2, inserted delays in the IEC 104 data between the DRZC and the FIU. Delays in this communications path were shown to cause the communication between the two devices to fail. With no communications between the DRZC and FIU, the DRZC cannot take any control actions.

This communications failure was apparent from the user interface screen of the network emulator, shown in Figure 5. The orange and blue lines in the figure show the data flowing between the FIU and DRZC in either direction. At the beginning of the plot, the delay was set to 0 ms with data flowing continuously and reliably in either direction. At 11:39:39 the communications delay in either direction was increased 50 ms and the communication data ceases to flow. Further investigation showed that the IEC 104 communications between the DRZC and FIU worked reliably for delays in both directions of up to 10 ms. However, delays of 11 ms or more would cause a similar communication failure to that shown in Figure 5. This was thought to be caused by a handshaking issue within the GE control equipment. When the delays were 10 ms or less, the devices would continue to communicate and there was no noticeable impact on the performance of the fast-balancing control.

Figure 5 Network Emulator user interface screen, showing network traffic between FIU (Port 1) and DRZC (Port 2)

Test 2 and Test 3 described in Table 2 both involved inserting delays in C37.118 data channels. The C37.118 data originates in PMUs on the distribution network (represented by virtual PMUs within the RTDS) and is first sent to the phasorprocessor (PDC) within the WAMS server, where it is aggregated and forwarded on to the DRZC. Inspection of the DRZC user interface showed that C37.118 data was arriving at the DRZC around 120 ms after it had been measured and sent from the RTDS, even with no delay added in the network emulator. The majority of this 120 ms delay, embedded within the control and network architecture, can be attributed to the phasor measurement process[4], and aggregation and forwarding processes[5] within the WAMS server. The communications delay in the physical network onsite at the HVDC Centre is thought to be minimal; ping tests between devices located at either end of the network showed approximate round-trip times for packets of data were a maximum of 5 ms.

The fast-balancing responses using the Test 2 and Test 3 communication delay test setups are summarized in Table 3. It shows the frequency deviation for both +10 MW and -10 MW load steps as varying communication delays from 0 ms to 90 ms were introduced using the network emulator. Delays of up to 50 ms did not appear to impact the performance of the fast-balancing control significantly. Meanwhile, delays of 60-80 ms showed the fast-balancing control becoming less effective at managing the frequency deviations during step changes in load. For delays 90 ms or longer the controller would reject PMU data measurements and stop taking control actions, therefore no longer delays were examined.

It may be noted that the configuration of the DRZC control process can be adapted to balance the speed and effectiveness of the control process against the capability of the communications infrastructure. The DRZC system configuration applied was designed according to the expected

[4] Measurement of a synchrophasor applies an analysis window to measured waveform data, and the timestamp is applied to the midpoint of the window. There is therefore an inherent delay related to the PMU measurement creation. This is typically around 35ms for measurements if the IEEE C37.118 P-class standard requirements are adhered to, but would be around 140ms for an M-class data stream.

[5] According to IEEE standard for PDC (IEEE C37.247-2019), “forwarding” of streams directly passes a data stream through the PDC, while “aggregating” compiles and time-aligns data from multiple streams before sending out a single stream. Forwarding tends to be used for time-critical control functions, while aggregation reduces the bandwidth and complexity of data exchange, mainly used in monitoring applications.

capabilities of a real-world wide area communication network and is typical of the performance experienced in other countries for power system control.

Table 3 Summary of fast-balancing results for communications delay tests

Comms Delay Test Setup	Delay (ms)	Minimum Frequency (During +10 MW step)	Maximum Frequency (During -10 MW step)
2	0	48.8	51.2
3	0	48.8	51.2
2	50	48.9	51.2
3	50	48.8	51.2
2	60	48.8	52.7
3	60	49.4	53.1
2	70	47.2	53.5
3	70	47.2	53.4
2	80	46.5	53.5
3	80	46.8	53.1
2	90	46.5	53.3
3	90	46.5	53.5

The results for both Test 2 and Test 3 communications delay set ups were similar, and the Test 2 results are shown in more detail. Figure 6 shows the system response to a +10 MW load step with 0 ms delay. As the 10 MW load is energized, the frequency shown in Figure 6(a) dips with the additional 10 MW instantaneously supplied by the Steven's Croft generator Figure 6(c). The fast-balancing control responds by adjusting the set point of the Minsca BESS and the Steven's Croft load bank, as seen in Figure 6(b) to limit the frequency deviation.

Figure 7 shows the system response to a +10 MW load step with 60 ms delay introduced using the Test 2 configuration. The response of the controller with the 60 ms delay is such that the set point values seen in Figure 7(b) have small changes after the load is energized not seen in Figure 6(b) which impact the electrical power output by the generator seen in Figure 7(c). The frequency deviation with 60 ms delay shown in Figure 7(a) has a larger oscillation than the similar result without delay shown in Figure 6(a). Additionally, the frequency takes longer to return to nominal frequency in the 60 ms delay case.

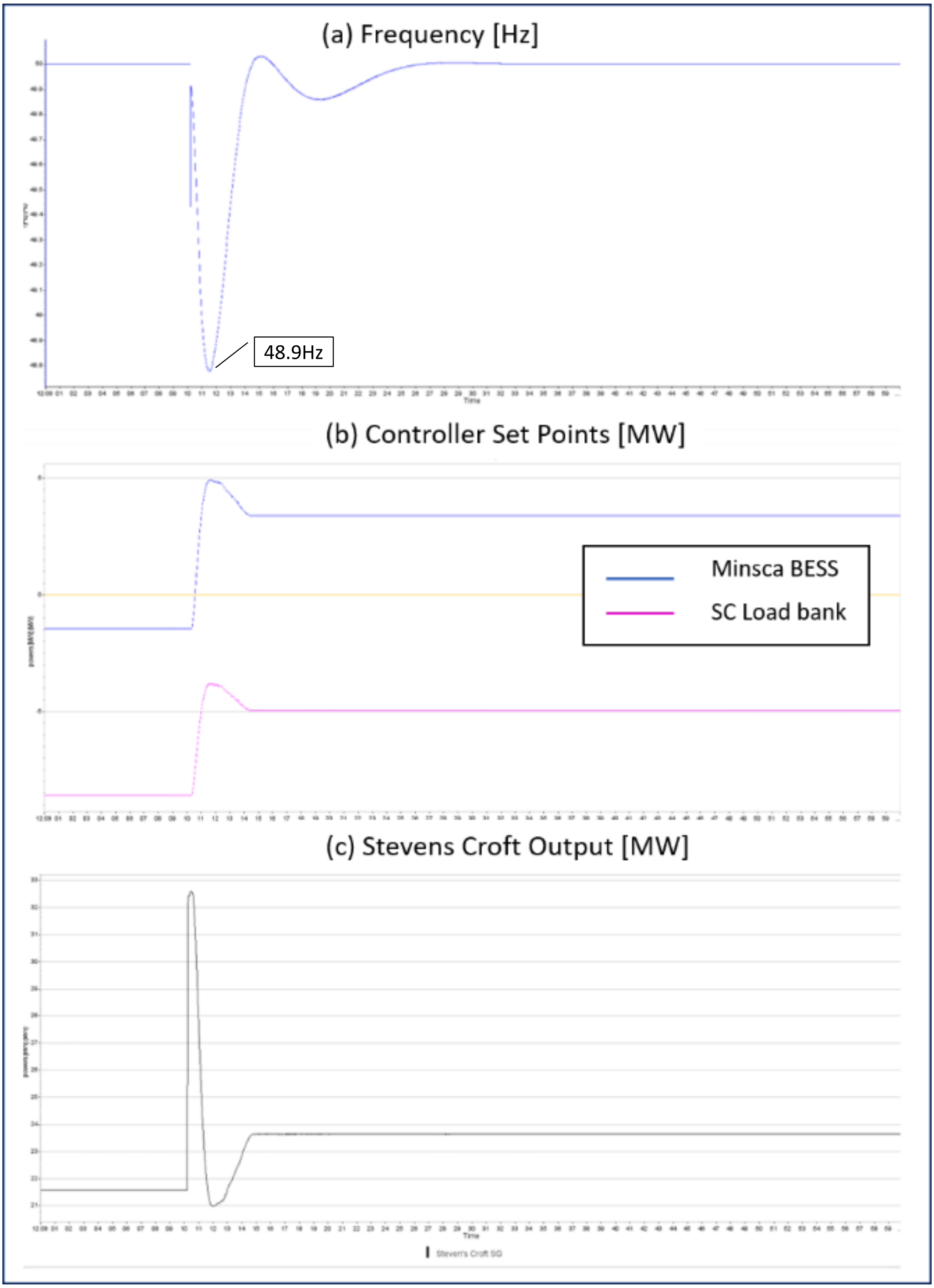


Figure 6 System response to a +10 MW load step (Delay Test Setup 2, 0 ms Delay, 1 min time axis)

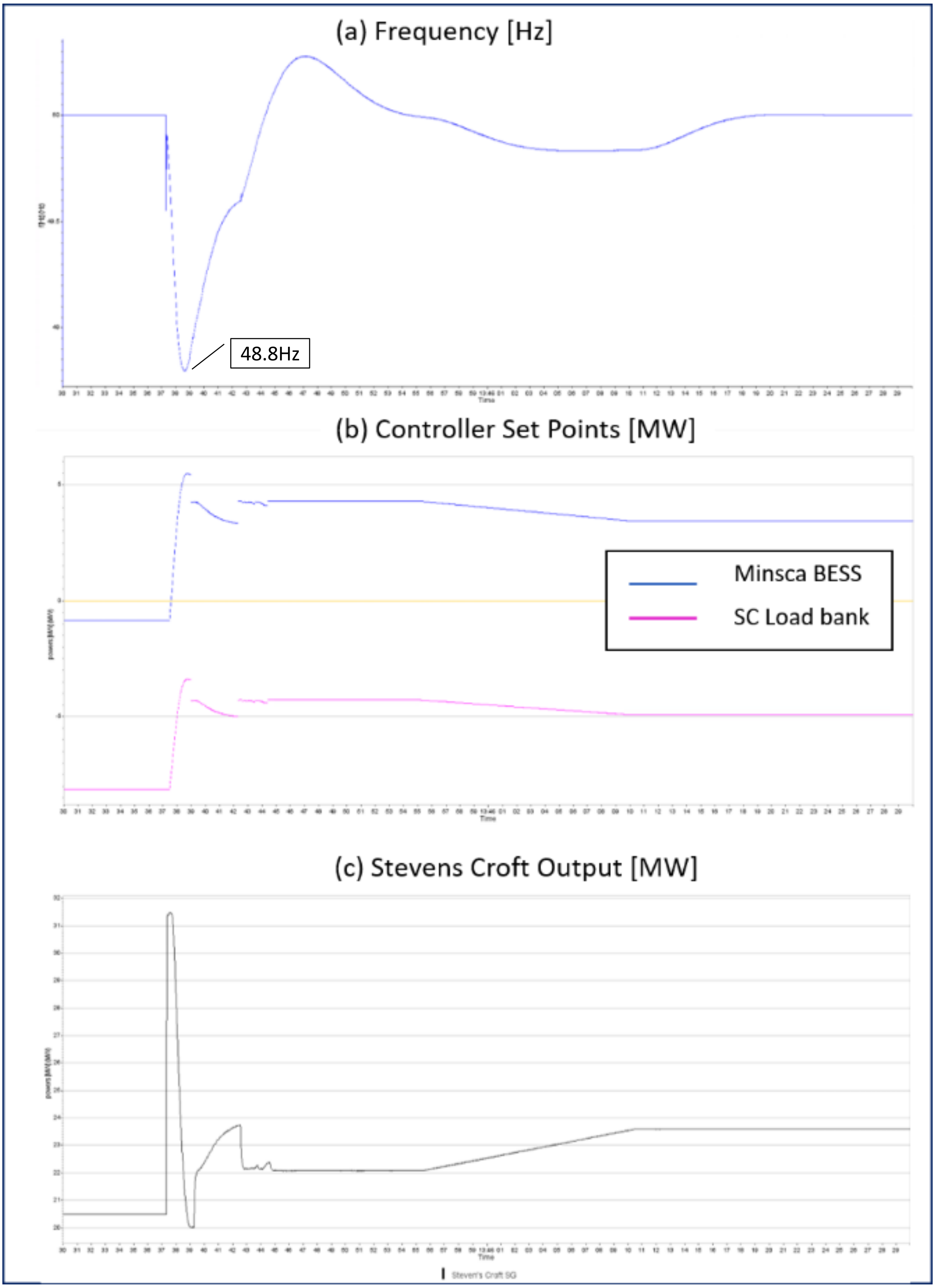


Figure 7 System response to a +10 MW load step (Delay Test Setup 2, 60 ms Delay, 1 min time axis)

Figure 8 shows the system response to a +10 MW load step with 90 ms delay introduced using the Test 2 configuration. In this case the C37 PMU data is rejected by the DRZC, and the controller takes no action, with no set points issued to the Minsca BESS or Steven's Croft load bank. It is worth noting that the data has arrived at the DRZC after 210 ms, due to the embedded delay of 120 ms caused by the control architecture, combined with 90 ms delay introduced by the network emulator. In this case the frequency plot Figure 8(a) and power output plot Figure 8(b) essentially show the response of the Steven's Croft generator without any fast-balancing control. It is perhaps worth noting that the frequency deviations seen in the 90 ms delay case where the controller took no fast-balancing control action, are similar to the frequency deviations seen in the 80 ms delay case where the controller was still active suggesting that with a delay of 80 ms the fast-balancing control is no longer useful. This is likely to be dependent on the generator parameters.

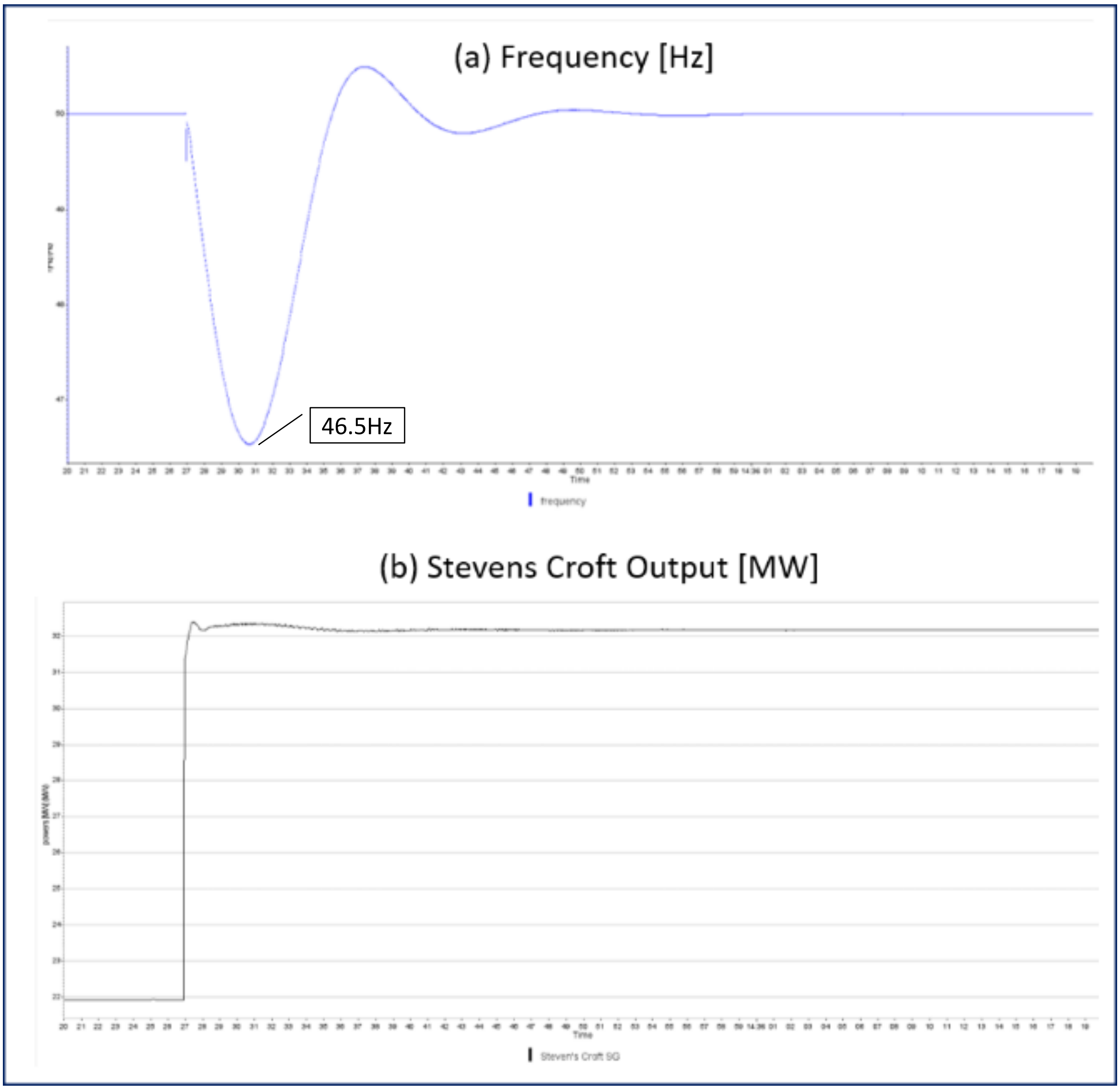
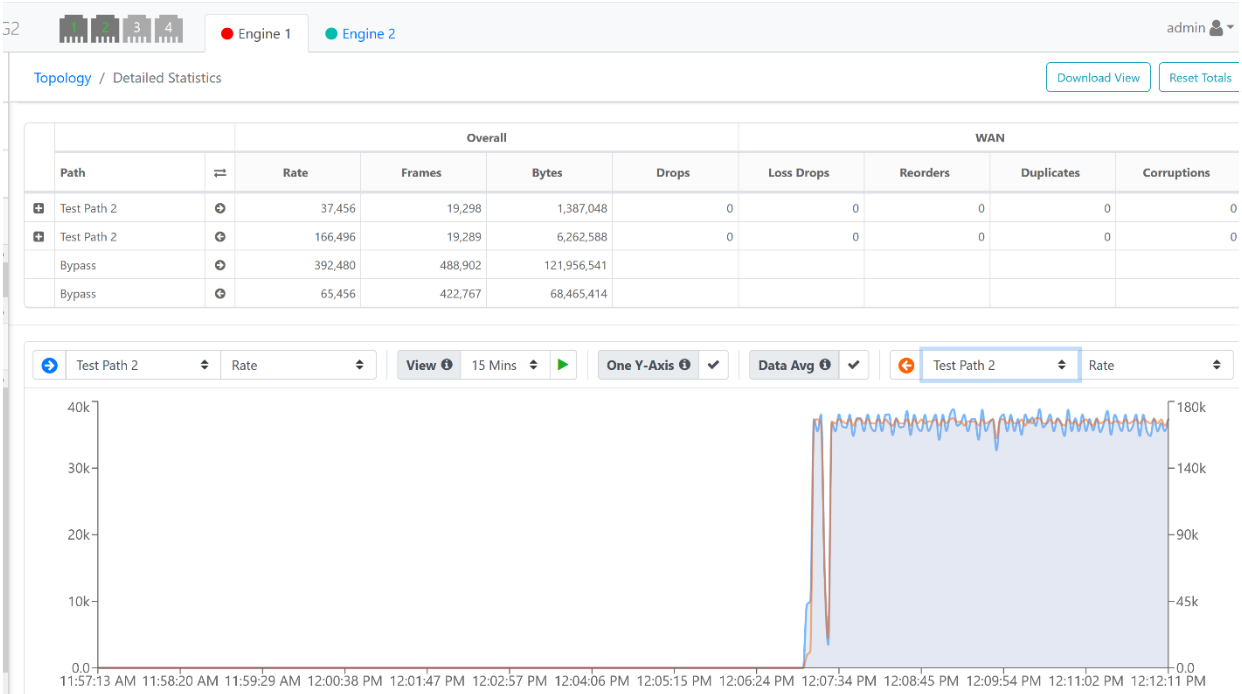


Figure 8 System response to a +10 MW load step (Delay Test Setup 2, 90 ms Delay, 1 min time axis)

5.2.4 Diagnosis and fixing of communication interruption due to delays

After tests run at the HVDC centre, further analyses were run to understand what was causing the drop of the IEC-104 link between FIU and DRZC. It was found that the main reason was a large number of commands issued by the master. Reducing the frequency of such commands by avoiding duplicates carrying the same value allowed a delay of 60 ms to be introduced without making the connection



drop.

Figure 9 IEC-104 data flow between DRZC and FIU after modifying the communication settings. The temporary drop corresponds to the introduction of a 60 ms delay per leg.

Further tests were carried out with delays equal to 100 ms, 150 ms, and 200 ms per leg. Communications held with delays up to about 150 ms. The frequency of commands was set to increase during transients, when setpoints are required to vary more often, so it is not possible to determine an exact threshold of acceptable delay.

5.2.5 Conclusions and Learning Points

Although the black start testing at the HVDC Centre merely confirmed performance of the DRZC already demonstrated in testing at GE, integration work to get to the stage where it would successfully run in the RTDS test environment resulted in a significant number of incremental improvements to the GE controller that would make it more robust. This included an improvement to how set points are issued to generators and balancing devices by the DRZC to avoid the possibility of gaps in signals/data causing instability or oscillations.

The full waveform simulation implemented in RTDS is intended to allow for modelling and testing of electro-magnetic transient (EMT) phenomena. While this may be an important consideration in overall design and implementation of a distribution restoration zone, such EMT behaviour is too fast to have a direct impact on the DRZC itself and therefore is not relevant to testing its performance. Using an EMT-level model in a platform like RTDS introduces additional complexity to the modelling, which may result in additional problems, adding time to the testing process. For a control system such as the DRZC, it will in most cases be more appropriate to use a phasor-domain power system model, such as that implemented in GE's Opal-RT test environment.

The delay testing revealed a vulnerability to the IEC 104 communications link between the FIU and DRZC which was resolved through updating the configuration for IEC104 communication. The issue would also affect second IEC 104 link between FIU and FEP and the same resolution applied.

The delay testing also showed that delays in receiving the C37 PMU data at the DRCZ would impact the performance of the fast-balancing control. However, in this case the delay in C37 PMU data is heavily impacted by a delay of 120 ms embedded within the control architecture, caused by the PMU measurement, aggregation and forwarding of PMU data through the phasorprocessor (PDC) at the WAMS server. The PMU measurement delay is optimised by the use of IEEE C37.118 P-class phasors. The DRZC control could be made more robust to delays in receiving C37 PMU data by using data forwarding rather than aggregation or sending PMU data directly to the DRZC without this intermediate step, however secure encrypted data transfer between sites requires the use of aggregated streams.

Delays in the communication network were shown to affect the performance and reliability of the DRZC in a number of ways, as shown in this report. This should be considered when selecting the service requirements and specification for communication links used on site.

6. Future Roles in DRZC Testing and Validation

6.1 DRZC Vendor Test Processes

The vendor test process is intended to confirm that the control system and all components are operating according to the design and prove the performance prior to installation and commissioning in the live system. The vendor test processes include:

1. Confirming the intended operation of the DRZC equipment
2. Connectivity between the devices in the zone and communication with the DMS
3. Input and output signals interfacing the DRZC system to equipment in the field
4. Stable and responsive operation of the overall zone through the restoration process, aligned with the system design specifications
5. Intended interaction between the DMS system and the zone controller of the DRZC
6. Depending on whether DMS and DRZC are from the same vendor, integrated testing of the DMS and DRZC may be part of the vendor test process
7. Confirmation of correct installation of the system on the live network, proving communications and connectivity to the controlled devices.
8. Confirmation of maintenance updates if required following commissioning of the system

Of these tests, items 1-3 would involve open-loop testing with signal injection, and would not necessarily require a HiL test environment. Items 4-6 would require testing using the HiL environment. Items 7-8 involve validation of operation on the live network and involve pre-deployment testing before the more restricted testing that can be achieved on the live network.

6.2 Third Party Testing

Third party testing may be collaborative with the DRZC vendor, or independent.

The goal of collaborative third party testing with the vendor is to improve the performance and usability of the scheme, with the vendor and third party working together to design and run the testing process to yield useful learning and experience that would not be easily obtained by the vendor alone.

The goal of independent third party testing is validation of the operation of the system and identification of issues and problems. It can also be appropriate for benchmarking a reference system to quantify performance of the DRZC approach in zones with similar characteristics. This leads to clearer performance requirements and specifications for a business-as-usual rollout.

The use of free-form experimental testing by an independent third party without the vendor's participation is generally not advised. Without a clear route to use the testing to feed into improvements in the system performance, there is not a clear goal. Confidentiality restrictions may limit the ability to use the results in a meaningful way. A collaborative testing approach will generally be more constructive.

6.2.1 Collaborative Test Processes between Stakeholders

A collaborative test process approach will typically involve an independent testing party working with the vendor to gain insights and improvements in the scheme performance in different ways:

- Testing party develops a platform and models for the test process
- Testing party drafts a test procedure, commented by the vendor and other stakeholders
- Vendor(s) install and configure the equipment to interface with the test platform
- Testing party carries out the tests, normally with support from the vendor, ensuring that both the test platform and the system under test are operating as expected
- Testing party reports on the test results
- Issues arising from the test process are reviewed and addressed, and test re-runs may be applied
- The HiL platform and deployed system, together with the scenarios, can be used for demonstration, training and wider stakeholder review

6.2.2 Third Party Validation of a Distribution Restoration System

A second use case of third party testing is for validation of operation of a DRZC system according to an agreed design and test methodology. Whether such a test stage is required will depend on the requirements of the network owner and contracted parties to deliver the service.

In this case, the testing party would be responsible for the full development of the platform, test process, interfacing to the DRZC system and running of the tests. Although there should be an opportunity for the vendor to review and comment on the test process in advance of the testing, the responsibility for the process would lie with the third party testing organisation.

In this case, it is important that there are clearly defined pass/fail criteria, so that the tests are repeatable and issues can be documented, resolved and re-validated.

The experience from the Distributed ReStart process suggests that it is challenging for an independent party to create the environment, design test scenarios, connect the DRZC system and run a test process without active participation of the vendor.

6.2.3 Benchmarking for Reference Designs

Each distribution restoration zone will have site-specific details, but there will be some similarities between zones with specific characteristics. A number of reference systems could be developed that would be applicable for different types of networks. For example, the type of anchor, the amount of inertia, the fast-balancing equipment available (BESS or load banks) and the number and size of loads could be used to define key reference systems.

A DRZC design could be developed as a benchmark for each of the reference systems. The benchmark would then be tested and characterized in terms of the dynamic performance that can be achieved by the control capability, and its resilience to disturbances assessed.

Improvements to the DRZC processes can be evaluated relative to the reference designs, and the references can be used to develop and refine standard requirements for a zone.

A third-party testing laboratory would be well placed to carry out the benchmarking, and a vendor-neutral benchmark would be a valuable contribution to business-as-usual rollout.

6.2.4 Limitations of Third-Party Testing

It may be noted that configuring the test platform and the scenarios for testing requires a specific skill set, and can be a time-taking process. It would be challenging to create a third-party test environment for every business-as-usual instance of a zone.

Third-party testing is likely to be time consuming due to:

- Adequate time needs to be allowed for control equipment and the test platform to be interfaced and adapted to each other, as well as modelling the power system.
- The third-party carrying out the testing and the manufacturer both have limited visibility and control over each other's equipment which makes debugging and fault finding with the complete test system time consuming.
- Setting up the controller and test platform takes skills and knowledge from a number of niche subject areas, such as power system operation/modelling and hardware set up. For example, debugging issues with communication protocols typically requires input from both the manufacturer, the third-party carrying out the testing, and support from the manufacturer of the real-time test equipment.
- All power system models involve a number of base assumptions about how devices will be represented and used/operated. This means controllers may need to be retuned for different test systems.
- In this particular case, there have been issues providing a suitable internet connection for GE to remotely connect to their equipment hosted at the HVDC Centre. This has made it harder for GE to work on their equipment, as they had to come to the HVDC Centre even to make relatively small changes.

It is expected that is appropriate to consider third party testing as a form of type-testing for the reference systems described above.

For individual zone designs and implementations specific to the resources in a particular network, it is expected that a vendor-based testing would be a more efficient process.

7. Conclusions

The testing process for a DRZC scheme is a key element of the learning from the Distributed ReStart project and a robust testing approach is necessary for the rollout of business-as-usual zones. Since wide area control on electricity distribution networks is a relatively recent and expanding field, the testing procedures are new and not yet standardized. Given the flexibility of adapting the zone control to different topologies and controllable resources, designing and applying a DRZC system test process is a significant part of a DRZC project.

Real-time Hardware-in-the-Loop testing is a necessary part of the testing process, as it enables the overall system to be tested in a closed-loop configuration. Many more scenarios can be applied compared with the testing that can be done in the live environment, allowing a wider range of testing of the stability and response of the network when the DRZC control is included. As well as testing the algorithms and logic of the control system, it is also useful for demonstration and development of the system including the human interface and network control through the DMS system.

HiL testing is not the only form of testing, and this report describes the role of HiL tests in the wider context of the various testing that is required in order to commission a DRZC scheme. However, the focus of the report is on the HiL tests.

Two HiL test processes have been demonstrated in Distributed ReStart using two separate platforms and models. One was developed by GE as the vendor and used in development, testing and demonstration for workshops with the stakeholders. The second was implemented by the HVDC Centre as independent testing. This serves to illustrate the different roles of vendor testing and third party testing.

Development of stable and usable models in a HiL environment and linkage to the DRZC and DMS is a technical challenge. The time taken to plan and implement HiL testing is significant and should not be replicated unnecessarily. In the rollout to business-as-usual deployment of DRZC testing, it is recommended that a rigorous vendor testing process will suffice for repeating rollout of DRZC schemes with similar characteristics.

Independent third party testing is valuable and should be applied in the following situations:

- As a benchmark for reference of zones with similar characteristics of network and resources
- For a new or significantly modified DRZC design compared with established designs
- For development and refinement of specifications for DRZC systems
- For interfacing between systems supplied by different vendors

The full test process and results of the GE vendor tests was described in detail in the previous test report ([1]), and a summary of outcomes is included in Section 5.1 of this document. The further results from the HVDC Centre independent tests are also included in this document in Section 5.2.

8. References

[1] “DRZC Factory Acceptance Testing 1 Report,” GE Digital, April 2022 [https://www.nationalgrideso.com/future-energy/projects/distributed-restart/key-documents]

[2] https://www.apposite-tech.com/products/netropy-network-emulation/

Appendix A. Detailed Description of RTDS™ Testing

A.1 Communications Delay Testing (Fast Balancing Control)

A.1.1 Controller Topology

A block diagram showing the elements of the GE DRZC test setup, and the protocols used to communicate between different elements is shown in Figure 2 in the main report. The setup at the HVDC Centre uses a Real Time Digital Simulator (RTDS®) running an Electromagnetic Transient (EMT) network model developed in the RSCAD software. The rest of the GE hardware setup and comms channels are similar to those used during the previous FAT tests [1].

A.1.2 SPEN Test Requirements

SPEN proposed inserting delays to the communication channels as described in Table 4. The table shows four separate tests to be applied to the fast-balancing control. Each row describes one of the comms protocols used to link the components of the controller shown in Figure 2 in the main report.

Table 4 Proposed Comms delay tests provided by SPEN

Test	Link (Bidirectional)		Protocol	Bandwidth	Latency	Use Case
1	PhC DRZC	PhC FIU	T104 encrypted	5 kbps (?)		Fast Balancing
2	PhasorPoint (WAMS)	PhC DRZC	IEEE C37.118 with TLS	180 kbps (?)		Fast Balancing
3	PhasorPoint PDC	PhC DRZC	IEEE C37.118 with TLS	180 kbps (?)		Fast Balancing
4	PhasorPoint PDC	RTDS	IEEE C37.118	180 kbps (?)		Fast Balancing

A.1.3 Hardware Configuration

The hardware setup at the HVDC Centre is shown in Figure 10. The FIU, DRZC, ADMS, WAMS, FEP and GPS clock are all located in the Protection Workshop. Meanwhile, the RTDS hardware is in the RTDS room. The RTDS has two ethernet ports: one C37 PMU interface, and one 61850 GOOSE interface. In addition, there is an internet router used to provide an ADSL connection for remote access located in the plant room. The devices are linked together using switches and ethernet cables as shown.

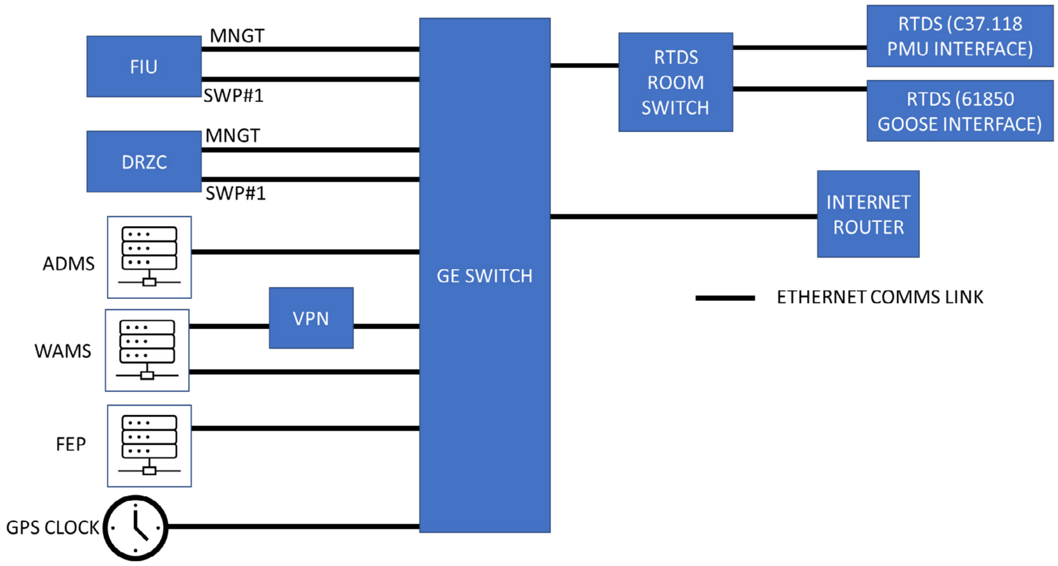


Figure 10 Communications Setup at the HVDC Centre

A.1.4 Adding Communication Delays Using a Network Emulator

The HVDC Centre used a Netropy 10G2 Network Emulator [2]. This can be inserted into any of the physical ethernet links using a set of paired ethernet ports which are linked together within the emulator.

Paths between the paired ethernet ports can be configured within the emulation software:

- "Test Paths" are defined within the setup software using various parameters including bandwidth, delay, and error rates.
- Alternatively, data can be sent via a "Bypass Path", which is a simple path between the paired ethernet ports without any artificial bandwidth constraints, delay or error added.

There are ways of selecting which data is sent on different paths within the emulator, provided that the packets of data are clearly addressed.

External devices are defined as "endpoints" within the emulation software using fixed characteristics such as their IP address. These devices or endpoints can be connected/mapped to particular paths in the emulator using endpoint rules. For example, all data between one endpoint address and another endpoint address can be sent via a particular path.

A.1.5 Tests Using the Network Emulator

Mapping the test requirements of Table 4 to the communications hardware in Figure 10, results in a slightly reduced set of tests because the PhasorPoint PDC listed in Table 4 is in fact implemented within GE's WAMS server. This means that from a communications testing perspective test 2 and test 3, as defined in Table 4, are indistinguishable.

In addition, the network emulator described in section A.1.4 has some limitations with how data can be selected /filtered within the network emulator. Network data was subjected to delays by applying endpoint rules based on each device's IP address. This in fact applied delays to all packets of addressed data sent between the two IP addresses of the devices under test regardless of protocol. (Although not applicable to the proposed tests, selecting/filtering broadcast data, such as 61850 GOOSE message data, based on specific IP addresses could be problematic).

Table 5 Proposed Tests Using the Network Emulator

Test	Link (Bidirectional)		Protocol
1	DRZC	FIU	IEC 104 encrypted
2	WAMS	DRZC	IEEE C37.118 with TLS
3	WAMS	RTDS	IEEE C37.118

Test 1 and Test 2 from Table 5 were carried out by installing the network emulator between the DRZC and the GE Switch, as shown in Figure 11.

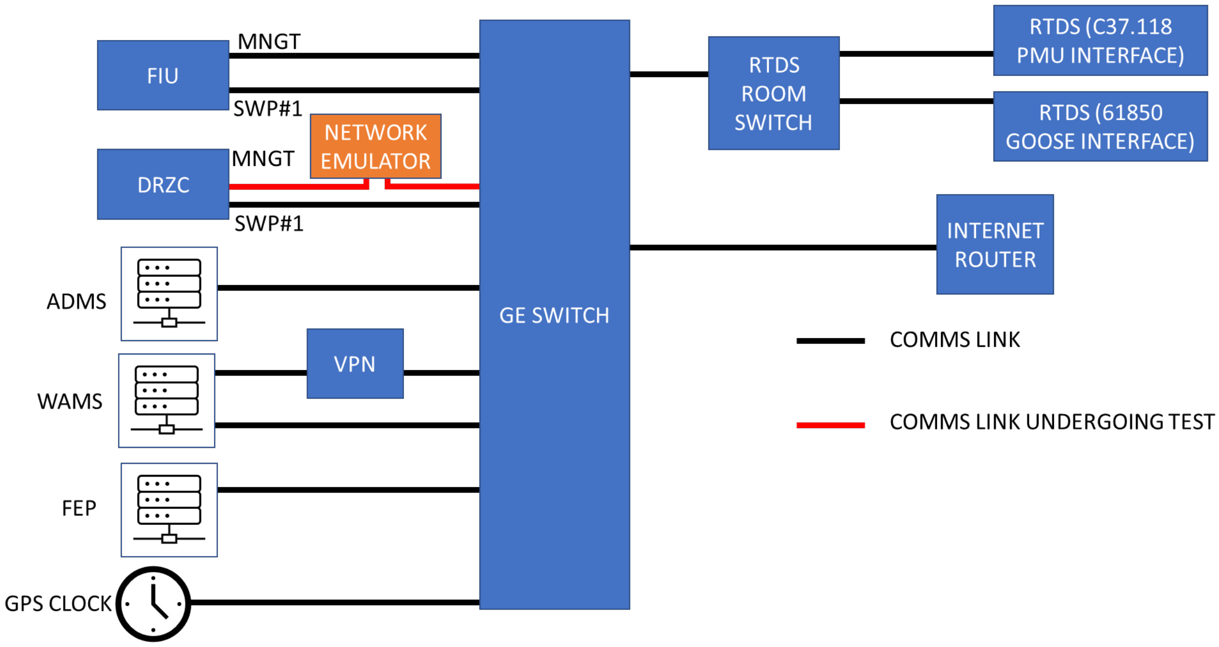


Figure 11 Network Emulator Test Position A (for Tests 1 and 2)

For Test 1, all data was sent via the “bypass path” without delay by default. Network data between the DRZC and the FIU was directed over the “test path” by filtering data using endpoint rules with the IP addresses of each device.

For Test 2, all data was sent via the “bypass path” without delay by default. Network data between the DRZC and the WAMS server was directed over the “test path” by filtering data using endpoint rules with the IP addresses of each device.

Test 3 from Table 5 was carried out by installing the network emulator between the GE switch and the RTDS room switch, as shown in Figure 12.

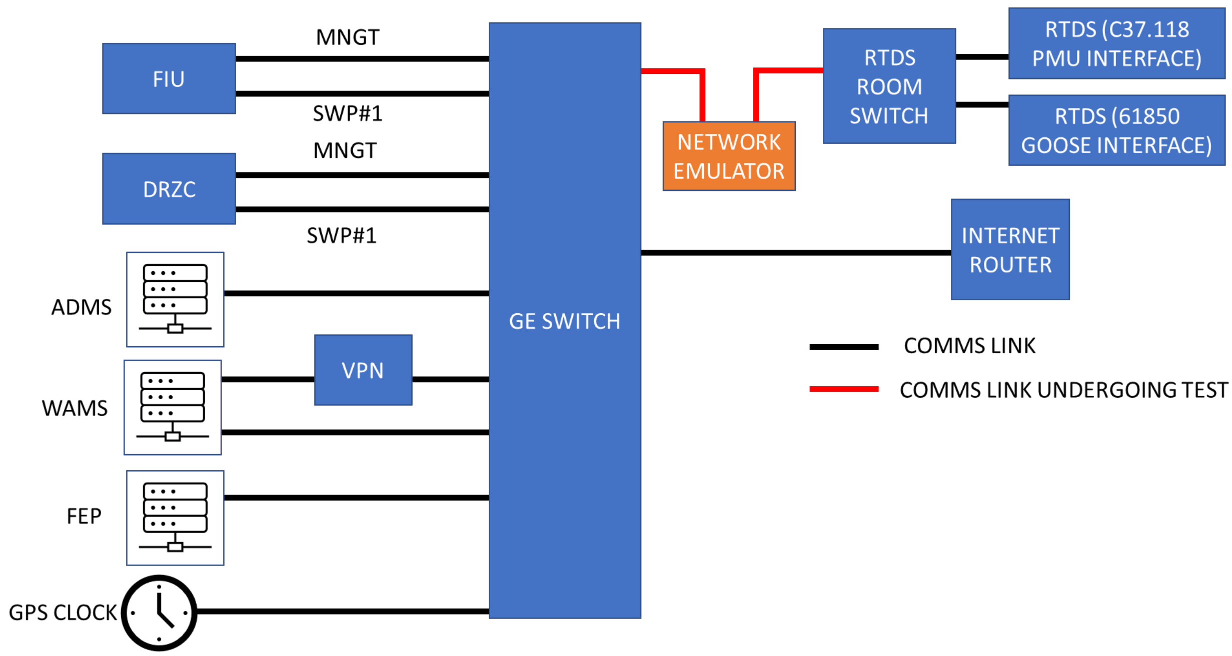


Figure 12 Network Emulator Test Position B (for Test 3)

For Test 3, all data was sent via the "bypass path" without delay by default. Network data between the RTDS PMU interface and the WAMS server was sent over the "test path" by filtering data using endpoint rules with the IP addresses of each device.

Appendix B. DRZC Parameter Tuning for a Zone

Each PR and PBC unit needs to be assigned power level thresholds for the Slow Balancing action. Those thresholds are currently hard-coded into the DRZC, but in a BaU scenario they will be modifiable by the ADMS.

Two fast balancing parameters need tuning according to the latencies and droop parameters of PR units present in the area.

A more detailed description of the DRZC control scheme can be found in [1].

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